Pre-1919 suspended timber ground floors in the UK: estimating in-situ U-values and heat loss reduction potential of interventions

Sofie Liesbet Jan Pelsmakers

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Declaration

I, Sofie Liesbet Jan Pelsmakers, confirm that the work presented in this thesis is my own. When information has been derived from other sources, I confirm that this has been indicated in the thesis.

Sofie Pelsmakers

July 15th 2016

Abstract

Space heating demand in dwellings accounts for around 13% of the UK's CO_2 emissions. In support of the UK's carbon emission reduction targets, the UK's existing housing stock would benefit from its thermal performance being characterised. This would facilitate decision-making in the reduction of space-heating energy demand through retrofit. Approximately 25% of the UK's 26 million dwellings pre-date 1919 and are predominantly of suspended timber ground floor construction, the performance of which has not been extensively investigated at present. While under-floor insulation uptake may increase under future government policies, the actual thermal performance of suspended timber ground floors and the implications of insulating them are poorly characterised at present.

This PhD research used in-situ heat-flow measuring techniques and the research improved and added knowledge and understanding to the methodological approaches of in-situ estimation of floor U-values, the in-situ estimated U-value of a small number of suspended timber ground floors and the effect of some insulation interventions.

Findings highlighted a significant variation in 'point' U-values across the floor with increased thermal transmittance observed along the exposed perimeter and near airbrick locations. This additionally highlighted that obtaining 'whole' floor U-values from a limited number of measured point locations on a floor with large heat-flow variations is challenging. Furthermore, insulation interventions significantly reduced floor U-values and generally a significant disparity was found between modelled and measured U-values. Current models appeared to underestimate the 'whole' floor measured U-value for the floors monitored and this disparity reduced the better insulated the floor.

Using current floor U-value models might result in misguided retrofit strategies due to the observed disparity between in-situ estimated and modelled floor U-values as found in a small sample in this study. If these observations are more broadly confirmed in the pre-1919 housing stock, it could have significant implications for policy and retrofit decision-making.

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Nomenclature

Abbreviations

AIVC	Air Infiltration and Ventilation Centre
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
ATTMA	Air Tightness Testing & Measurement Association
BSI	British Standards Institution
BRE	Building Research Establishment
BREDEM	BRE Domestic Energy Model
BREVENT	BRE Ventilation model– now no longer in use
CCC	Committee for Climate Change
CEN	European Standardisation Committee
CERT	Carbon Emissions Reduction Target
CESP	Community Energy Saving Programme
CIBSE	Chartered Institution of Building Services Engineers
DCLG	Department of Communities and Local Government
DECC	Department of Energy and Climate Change
DIY	'Do It Yourself', i.e. without expert input
ECO	Energy Companies Obligation
EH, Salford EH	English Heritage, now renamed to Historic England; also refers to the Salford Energy House (EH)
EST	Energy Savings Trust
EPS	Expanded Polystyrene
HTT	Hard To Treat
IEA	International Energy Agency
IR	Infrared
ISO	International Organisation for Standardisation
JCGM	Joint Committee for Guides in Metrology
LEB	Low Energy Buildings database
MVOCs	Microbial Volatile Organic Compounds
NDA	Non-disclosure agreement
NBT	Natural Building Technologies
NBS	National Building Standards
OAT	One Variable at a Time
PHPP	PassivHaus Planning Package
PIR	Polyisocyanurate
PMV	Predicted mean vote
PPD	Predicted Percentage of Dissatisfied
PUR	Polyurethane

RBKC	Royal Borough of Kensington and Chelsea
RdSAP	Reduced SAP
RH	Relative Humidity (%)
SAP	Standard Assessment Procedure
SBSA	Scottish Building Standards Agency
SDOM	Standard Deviation of the mean, or also SE or standard error
TSB	Technology Strategy Board – now renamed to Innovate UK
VTT	The Finnish Technical Research Centre
UCL	University College London
Up-value	Point U-value: is the term used as a generic description of the small area-based in-situ U-value measurement on a certain location on the floor
WF	Woodfibre
WMC	Wood Moisture Content
WUFI-BIO®	A biohygrothermal model developed by Fraunhofer
WUN	World University Network
XPS	Extruded Polystyrene
ZCH	Zero Carbon Homes

Main symbols

α	Ventilation opening area (m^2) per m exposed perimeter	m^2/m
A	Surface area	m^2
Ach^{-1}	Airchanges per hour	
b	Floor width/breadth (shorter floor dimension)	m
B'	Characteristic dimension of the floor and is the area divided by half the exposed floor perimeter	m^2/m
d_g, d_t	The total equivalent thickness of the ground for suspended and solid ground floors respectively	m
d_w, w	Foundation wall thickness	m
d_x	Is the fractional or absolute measurement uncertainty	% or $Wm^{-2}K^{-1}$
ε	Emissivity of surface	
E_{Sen}	Unique heat-flux instrument calibration correction factor	mVm^2W^{-1}
f_w	Wind shield factor – constant	
hf	Height of the top of the floor surface above external ground level	m
h_c, h_r	Convective and radiative surface coefficients respectively	$Wm^{-2}K^{-1}$
h_{ci}, h_{ce}	Convective surface coefficient at internal (or external, well-ventilated surfaces) and external surfaces respectively	$Wm^{-2}K^{-1}$
HF1, HF2,..	Heat-flux sensor location 1, 2,...	
H1, H2, H2a, H3,..	Hypotheses	
k or λ	Thermal conductivity	$Wm^{-1}K^{-1}$
λg	Soil/ground conductivity	$Wm^{-1}K^{-1}$
lf	Long dimension of the floor plate	m
$L1$, $L2$	Distance to the bay wall and gable wall in The Salford Energy House respectively	m
mV	millivolt	
σ	Stefan-Boltzmann constant (= 5.67×10^{-8})	$Wm^{-2}\ K^{-4}$
P	Exposed floor perimeter	m
P/A	Exposed perimeter to floor area ratio	m/m^2
q	Heat-flux density	W/m^2
Q_c, Q_{cv} Q_r	Conductive, convective and radiative heat-flow respectively	W
R, $R1$, $R2$,...$Rt1$, $Rt2$,...	Thermal Resistance or R-value	m^2KW^{-1}
R_{ig}	Resistance of the insulation between floor and ground – zero in uninsulated suspended floors	m^2KW^{-1}
R_f, R_g	Thermal resistance of the floor	m^2KW^{-1}
R_c, R_r	Thermal resistances from the convective and radiative components	m^2KW^{-1}
R_e, R_v	Thermal resistance of the earth and ventilation resistance respectively	m^2KW^{-1}
R_s	Surface thermal resistance	m^2KW^{-1}

R_{Se}	External surface thermal resistance	m^2KW^{-1}
R_{Si}	Internal surface thermal resistance	m^2KW^{-1}
$R, R_1, R_2,...R_{t1}, R_{t2},...$	Thermal Resistance or R-value	m^2KW^{-1}
R_{est}	Is the in-situ estimated thermal resistance (excluding surface thermal resistances)	m^2KW^{-1}
R_T	Is the total in-situ estimated thermal resistance of the element, including surface resistances	m^2KW^{-1}
R_t	Is the calculated total thermal resistance, including surface resistances	m^2KW^{-1}
sd	Standard deviation, taken to represent the natural variability of hourly or daily mean in-situ measured U-values	% or $Wm^{-2}K^{-1}$
ΔT	Temperature difference between the internal and external environment	ºC
T_i, T_e	Internal and external temperatures respectively	ºC
T_{ia}, T_{ea}	Internal air and external air temperatures respectively	ºC
T_{Si}, T_{Se}	Internal surface temperature and external surface temperatures respectively	ºC
T_o, T_s	Temperature of the object and temperature of the surroundings respectively	ºC
U	Thermal transmittance, U-value	$Wm^{-2}K^{-1}$
U_{mean}	The total mean in-situ estimated thermal transmittance (mean of ratios)	$Wm^{-2}K^{-1}$
U_{est}	The in-situ estimated thermal transmittance	$Wm^{-2}K^{-1}$
U_g	Thermal transmittance of the ground	$Wm^{-2}K^{-1}$
U_f	Thermal transmittance of the floor (floor surface to void)	$Wm^{-2}K^{-1}$
U_w	Thermal transmittance of the foundation wall	$Wm^{-2}K^{-1}$
U_{wf}	Whole floor U-value	$Wm^{-2}K^{-1}$
V_f	Ventilation rate of the suspended floor	m^3/s
v	Average windspeed	m/s

Chapter 1: Introduction

1.1. Introduction

This chapter sets out the background and context of the research and motivation and also details the aims and scope of the study and provides an overview of the thesis structure.

1.2. Context

The burning of fossil fuels releases carbon dioxide which significantly contributes to global warming (IPCC, 2013, Stott, 2010). To curb global warming, the UK has committed to ambitious carbon reduction targets of 80% by 2050 (from 1990 levels) in the Climate Change Act 2008 (DECC, 2009). However, to meet overall emission reduction targets of 80%, it has been argued that the residential sector will have to meet higher carbon reduction standards of 88-91% (EC, 2011).

Around 50% of the UK's total CO_2 emissions are attributed to the construction and operation of buildings (Mackenzie, 2010). While ~27% of the UK's carbon emissions is attributed to the domestic sector alone (DECC, 2015d), between 50-65% of this is from dwelling space heating (DCLG, 2006, Palmer, 2011). Reducing carbon emissions associated with domestic space heating is a key aspect of the UK's planned transition to a low carbon economy (DECC, 2009, DECC, 2011a, DECC, 2012a).

Significantly, the UK has one of the oldest and least efficient housing stocks in the developed world. Approximately one third (Boardman, 2005, Cook, 2009, Stafford, 2011) of its ~ 26.9 million dwelling stock was built before 1940 (ONS, 2011). Seventy to 85% of existing UK housing is expected to still be in use in 2050 (SDC, 2006, Power, 2008, Killip, 2008), with an estimated 4.9 million dwellings built pre-1919 in England alone (DCLG, 2012) and 6.6 million in the UK (Thorpe, 2010). Generally, pre-1919 dwellings are of solid walled construction and tend to have larger floor areas (DCLG, 2012) and are estimated to have - per m^2 floor area per year - a mean space heat demand of about 14% greater than un-insulated cavity-walled dwellings and ~ 40% more than post-1990 constructed dwellings (DCLG, 2009).

1.2.1. Carbon reduction policies

Increasing energy efficiency in existing dwellings is one of the key strategies to meeting the UK's carbon reduction targets (DECC, 2012a, Mackenzie, 2010, Lowe, 2007a) and strategies to do this includes upgrading pre-1919 dwellings to low carbon standards by 2050 (DECC, 2009), which includes insulating ground floors (Power, 2008). Carbon reductions of 50-70% have been obtained in dwellings after insulating floors, walls, windows and lofts and installing new efficient boilers (Gentry, 2010), while Lowe (2007a) suggests that a combination of different fabric insulation and more efficient heat-supply could achieve similar carbon reductions. Additional benefits to upgrading the housing stock may include reduced fuel poverty and increased occupant thermal comfort (Hamilton, 2011, Bernier et al., 2010, Rock, 2013, Thorpe, 2010).

In the UK, carbon reduction targets have been underpinned by previous government policies such as 'Zero Carbon Homes' for new dwellings (ZCH, 2011) and the Green Deal and ECO-policy for existing buildings and their predecessors CERT, CESP and Warm Front (DECC, 2011b, Ofgem, 2013). The current ECO-policy is an obligation on large energy companies to install energy efficiency measures for certain consumers and communities, fully or part-subsidised by the companies (Ofgem, 2015). These policies aim to increase the rate of retrofit (DECC, 2011b, Mallaburn and Eyre, 2013) by improving the cost-benefit of interventions (Clinch, 2001). The Green Deal for example allowed building occupants to take out a pay-as-you-save loan to finance certain energy efficiency improvements, assuming the loan could be paid back from the predicted energy savings (DECC, 2011c, CCC, 2011). However, the actual carbon reductions and cost-effectiveness of retrofit interventions is contingent upon the delivered improvement in thermal performance.

1.2.2. Pre-1919 housing stock profile

Pre-1919 dwellings were predominately constructed with solid brick walls (Rock, 2005, Baker, 2011b, DCLG, 2009) and suspended timber ground floors were the prevalent ground floor construction method (Rock, 2005) (p20, p138) until 1940 (BRE, 1998). The majority of the pre-1919 housing stock are likely to have insulated lofts (on average 100-199mm) and ~75% of the pre-1919 dwellings have double glazing (Gentry, 2010). In 2015 DECC (2015e) reported that just 4% of solid walls in the UK's pre-1919 properties are insulated.

At present the proportion of insulated floors is unknown (Boardman, 2005), though floor insulation uptake might have recently increased as this was a Green Deal and ECO approved[1] intervention measure and funding was available under several government funding schemes under certain conditions (DECC, 2015f, DECC, 2014).

A large proportion of the pre-1919 dwelling typology is classified as hard to treat (HTT) (Thorpe, 2010, DCLG, 2012), due to its lack of cost-effective retrofit options, disruption and difficulty to upgrade (Beaumont, 2007, Wetherill M., Dowson et al., 2012). Given that pre-1919 houses are considered at greater risk of damp and mould problems with about 18% requiring remedial measures of some kind (DCLG, 2010) (p79), thermal improvement to such dwellings need to be undertaken with care.

1.2.3. Suspended timber ground floors

There might be as many as many as 10 million uninsulated suspended timber ground floors in the UK (Dowson et al., 2012, Shorrock, 2005), though not all would be dated pre-1919. Yet the thermal performance of this element is not well characterised at present. Furthermore there is also no robust data available on the thermal upgrade potential of such floors. It is estimated that a large proportion of dwelling space heating is lost through un-insulated walls and insufficiently insulated roofs (50% and 20% respectively, (NEF, 2011)). The proportion of total dwelling heat loss from un-insulated ground floors depends on the overall dwelling fabric efficiency standard and the proportional exposed floor area. Hence there are a variety of estimates in the literature: NEF (2011), WCC (2012) and Rock (2013) estimate a typical proportional heat loss of 10% to 15% through the ground. Rickaby (2014a) estimates that for an uninsulated semi-detached 1930's house, proportional floor heat loss could be as low as 4%, due to its large proportion of uninsulated exposed wall surfaces.

This assumed small proportion of floor heat loss of the total building heat loss might clarify why floor insulation has not been of much importance in energy policies, which have been in favour of wall and loft improvements first. However, energy and carbon reductions are not the only reasons to consider upgrading such floors: a potential benefit of insulating ground floors might be associated with increased occupant thermal comfort - see Chapter 6.5.

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1 For explanation of Green Deal and Eco-policy, see Section 1.2.1.

The potential to decrease energy use and reduce CO_2 emissions through floor improvements was indicated by Green Deal assessments, where around 200,000 suspended ground floor insulation measures were recommended between January 2013 and June 2015, which was nearly 12% of all recommended measures (DECC, 2015b). Despite this, just over 8,000 floors had reportedly been insulated under the ECO-policy (or just 0.5% of all installed ECO measures between January 2013 and September 2015). Around 400 floors were insulated with Green Deal finance until September 2015 (DECC, 2015c); which is just 2% of all Green Deal financed installed measures and only about 300 under-floor insulations were installed with incentives under the Green Deal Home Improvement fund (DECC, 2015c).

As illustrated above and noted by DCLG (2009), the uptake of floor insulation is slow in both social and privately owned dwellings. The small estimated proportional heat loss from floors, and the disruptive nature of installing floor insulation (discussed further in Chapter 6) as well as long payback depending on insulation method might explain this slow uptake (Rickaby, 2014a, Dowson et al., 2012, Killip, 2011). Furthermore, given the small estimated proportional ground floor heat loss, retrofit strategies might exclude ground floor insulation installations and in doing so, significantly increase proportional floor heat loss - see Chapter 6.4.7. Harris (1997) estimates the proportion of floor heat loss up to 25% in well insulated dwellings where the ground floor remains uninsulated. Some recent Technology Strategy Board (TSB (2012)) Retrofit for the Future projects adopted this strategy and instead off-set the assumed ground floor heat loss with increased insulation elsewhere, reducing the disruption of taking up floor boards. However off-setting assumed heat loss might be problematic if this is underestimated, and might lead to missed opportunities for energy, cost and carbon savings.

Despite the recent withdrawal of the Green Deal and its incentives, the ECO-policy is in place until at least 2017 (DECC, 2015a). While only a small proportion of installed ECO measures were floor insulations, thousands of floors were still insulated. However the actual impact of doing so on heat loss reduction, thermal comfort and floor void conditions remains unknown, alongside the unknown benefits and consequences of any of the other efficiency measures. Insulating the millions of uninsulated floors in the UK housing stock might lead to potential large carbon savings (Shorrock, 2005, Power, 2008), supporting carbon reduction policies. It is therefore important to have a better understanding of the thermal characteristics of these floors and the effect of insulation interventions. Specifically, to make informed decisions both in terms of government policies and in terms of home-owner choices, more research is required into the thermal performance of existing floors, heat loss reduction potential of insulating floors and other possible benefits or unintended consequences. For an image of a suspended ground floor, see *Figure 1.*

Figure 1. a and b. Typical suspended ground floor construction with floorboards removed to reveal joists and void below (a) and with floorboards down after insulation between joists (b).

1.2.4. Disparities between predicted and measured performance

Recently, both in traditional and newly built constructions, significant disparities have been identified between predicted and actual performance (Baker, 2011b, Rhee-Duverne, 2013, Rye, 2011, Li et al., 2014, Bell et al., 2010). It was found that in-situ measured U-values of solid walls were in many cases lower than those predicted (BRE, 2014a, Baker, 2011b, Rye, 2011, Birchall, 2011, Li et al., 2014). A variety of reasons have been proposed for this performance discrepancy, such as: occupant/building technology interfaces, occupant behavioural influences, construction difficulties or errors, increased thermal bridging, inaccurate modelling tools and lack of knowledge about materials' in-situ thermal properties, including inadequate understanding of the specific construction methods used, especially of traditional buildings (Barrett M, 2006, Stevenson, 2010, Audenaert et al., 2011, Guerra Santin, 2011, Guerra-Santin, 2010, Summerfield, 2009, ZCH, 2013, Mumovic, 2009, NHBC, 2012, Bell et al., 2010, May, 2012, Kavgic et al., 2010). Thus, the carbon reduction challenge is intensified by this underperformance of many interventions (Crosbie and Baker, 2010, Hong, 2006, LeedsMet, 2009, Stevenson, 2010) and the low level of refurbishment (Boardman, 2005, Weiss et al., 2012, DECC, 2012d). This also raised questions about government policy and the expected cost-effectiveness of retrofit measures and assumed pay-back times (May, 2012, DECC, 2012c) and if very long, is unfavourable to investment (DECC, 2011d).

This further highlights the necessity of research in this area, as also noted by Shrubsole (2014) and this also raises questions about the actual thermal performance of suspended timber ground floors and the efficacy of retrofit measures. While an initial comparison between the few published in-situ measured U-values and calculated U-values for suspended timber ground floors suggests a large divergence between the two, it is unclear how robust direct comparisons are due to a combination of factors - see Chapter 2.4.

1.3. Research Motivation

While floor insulation uptake may increase under the ECO-policy, the actual thermal performance of suspended ground floors and the impact and the implications of insulating them are poorly characterised. The importance of understanding the actual versus the predicted performance of a construction element is crucial to ensure that carbon reduction measures are effective and achieve their intended carbon reductions (May, 2012, ZCH, 2013) and to ensure appropriate retrofit decision-making and intervention choices. For example, if predicted floor U-values overestimate the actual values, carbon reduction goals and financial pay-back of interventions would be jeopardised. Alternatively, if actual floor U-values are underestimated, insulating such floors might be inappropriately discouraged due to assumed low carbon reductions and financial payback, while the opposite may be true. In that case there would be a significant additional potential to reduce energy and carbon emissions from insulating such floors.

Alignment of predicted versus actual thermal performance is also important for stock models and energy-reduction scenarios, as illustrated by Li (2014). Different assumptions about fabric U-values leads to different assumptions about carbon reduction potential and cost-benefits of retrofit measures. Given the large number of properties with suspended timber ground floors, such assumptions might have a significant impact on building stock model outputs, which are used to inform carbon reduction policy and to inform funding for carbon reduction measures. Yet at present it is unclear what the *actual* U-values are of suspended timber ground floors. This PhD thesis aims to contribute to this area of research, as set out in more detail in the following section.

1.4. Research aim, scope and significance

The purpose of this PhD research is to investigate the thermal performance of suspended timber ground floors and how to estimate in-situ floor U-values; specific research questions and objectives are presented in Chapter 2.9. The research aims to gain and add to the understanding of the actual performance of uninsulated suspended timber ground floors and the heat loss reduction potential of interventions and what the benefits and drawbacks of insulating such floors might be.

In doing so, this research builds on existing knowledge and research, while also contributing additional and original knowledge to the field with regards to:

- Testing and development of in-situ floor heat-flux measuring methods (Chapters 3, 4, 5, 6);
- Supplementing in-situ heat-flux measurements of floors (Chapters 4, 5 and 6);
- Investigation into the efficacy of some heat loss reduction interventions (Chapter 6);
- Supplementing data on floor void and on thermal comfort conditions of (un)insulated floors (Chapter 6), however a detailed floor void and thermal comfort study and the impact of thermal discomfort on compensating energy-use are outside the scope of this PhD research.

As previously identified, little research is undertaken in this area and Salisbury at DECC (2013) identified floor heat loss reduction measures and their implications as one of four areas requiring urgent research as part of existing housing stock retrofit for UK Government. In support of retrofit decision-making at policy, industry and consumer level, the primary significance of this study is in contributing knowledge of in-situ measured floor U-values and robust measurement and analysis techniques, which are poorly characterised at present. In-situ U-value estimations of floor case-studies advance knowledge and insight, enable a critical review of comparison to present models and draw out practical monitoring and insulation installation issues. Furthermore, this research draws together a literature review of heat loss, thermal comfort and mould growth research specifically related to suspended timber ground floors. While this study has only undertaken a limited number of in-situ U-value measurements this is - as far as the author is aware at the time of writing - one of the most in-depth studies of suspended timber ground floors in the UK. However, given the limited time-scale and seasonality of the research, undertaking a large-scale survey of suspended timber ground floors and the investigation of many different insulation interventions are outside the scope of this PhD research and are highlighted for further research investigations.

Current research paper under review at the time of writing:
Pelsmakers, S., Fitton, R. , Biddulph, P., Swan, W., Croxford, B., Shipworth, D., Stamp, S., Calboli, F. , Lowe, R., Elwell, C.A., *Heat-loss from suspended timber ground floors: in-situ measurement, variability and uncertainty*, Energy & Buildings.

1.5. Thesis overview

This PhD thesis is presented in 7 chapters, as illustrated in *Figure 2.*: Chapter 2 presents a literature review of physical theory, theoretical models of ground floor U-values and a critical review of model assumptions and in-situ measurements of suspended timber ground floors. Additionally, thermal comfort theory specifically related to ground floor surfaces; insulation of floors and floor void conditions and mould growth risk are reviewed. Finally, the PhD research questions are presented.

Chapter 3 presents the research design and methodology divided into three distinct parts: Part 1 reviews available research methods to answer the research questions identified in the preceding chapter and justifies methods chosen. Part 2 presents and critically reviews in-situ U-value measurement protocols and uncertainty procedures in detail and presents the applied in-situ U-value estimation and uncertainty estimation techniques for this study. Finally, Part 3 gives a brief overview of the formulated research hypotheses and the primary data collected for the four studies undertaken and includes a discussion about sampling and research generalisability and ethics.

Chapters 4, 5 and 6 each set out the primary fieldwork undertaken, with each chapter presenting detailed research design followed by results and analysis and discussion of the analysis and results, including comparison to models and reference to physical theory and literature presented earlier.

The subject of Chapter 4 is a low-resolution pilot study in an occupied house (STUDY 1) which directly leads to high-resolution floor heat-flow measurements in an environmental chamber, the Salford Energy House (EH, STUDY 2). Knowledge and techniques gained from this high resolution floor study were then taken forward in an unoccupied and uninsulated field case-study dwelling (STUDY 4A), subject of Chapter 5. This chapter also gives a snap-shot of the case-study's floor void conditions pre-insulation.

Chapter 6 presents a pre-and post insulation pilot study (STUDY 3), followed by two insulation interventions of the field case-study house (STUDY 4B). This chapter also gives an overview of the thermal comfort and airtightness implications of insulating the case-study floor.

Finally, Chapter 7 briefly summarises the key research findings and draws the findings together through a discussion of the policy and practical implications of the findings and reflections on further research. Note that the work is presented in a logical rather than chronological order.

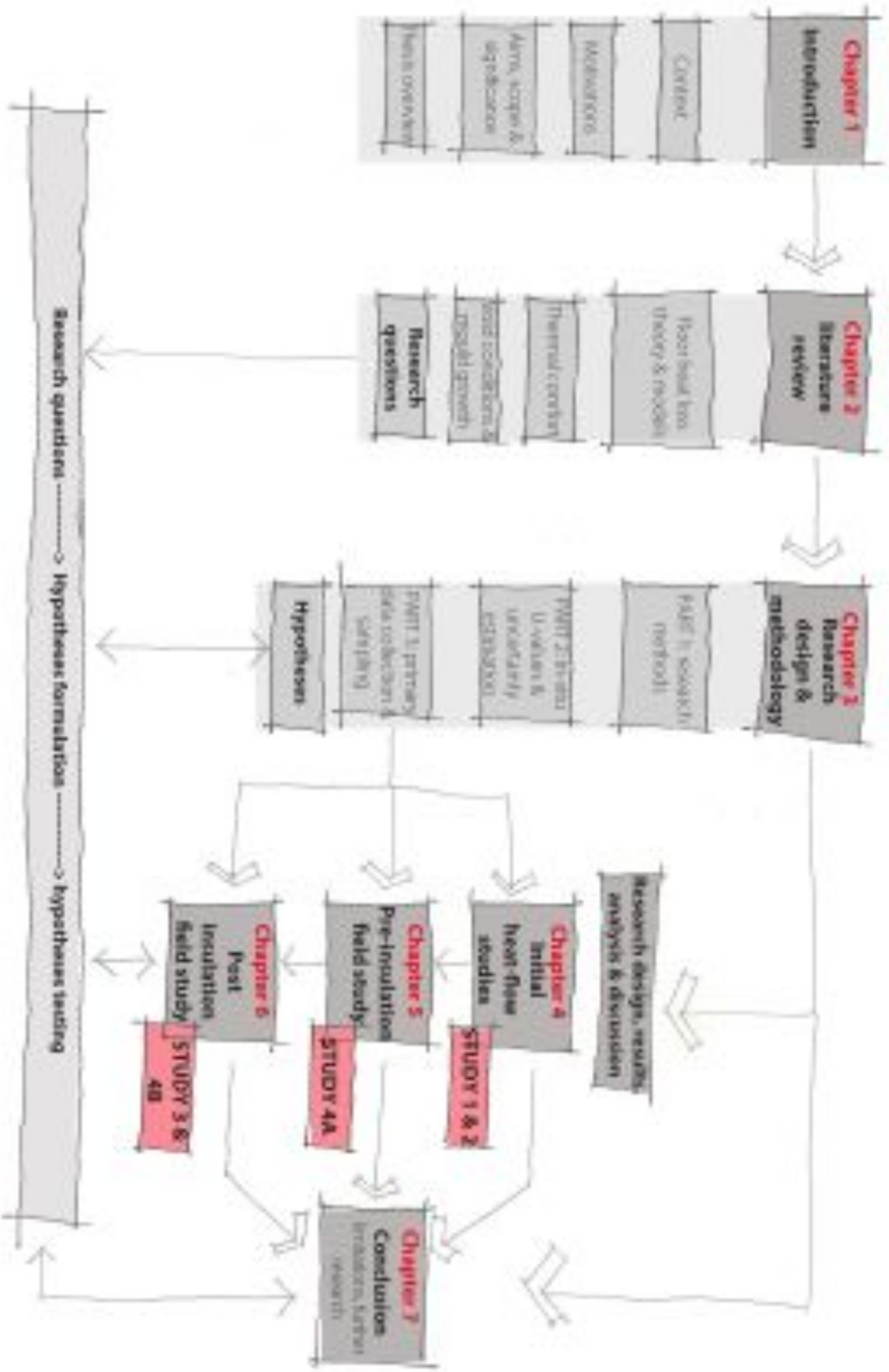

Figure 2. Flow diagram giving an overview of the main thesis components and studies.

Chapter 2: Literature review

2.1. Introduction

This chapter outlines the physical theory of ground floor heat-flow and how this is reflected in models, literature and published empirical results. First is presented a brief overview of solid ground floor heat-flow, followed by suspended timber ground floor heat loss theory, void air-flow and comparisons between published theoretical and in-situ heat-flow measured U-values. The chapter also explores current literature and research on the benefits of insulating floors, thermal comfort related to ground floors and the possible unintended consequences of floor insulation, in particular mould growth. The chapter concludes with the PhD research questions and objectives and definitions.

2.2. Floor heat loss: physical theory

Heat-flow through building elements depends on the temperature difference between the inside and outside environment of a construction and occurs by conduction, convection and radiation; mechanisms which are dependent on material properties such as material thickness, conductivity and surface colour but also moisture content and exposure to climatic conditions. The conductive component is expressed as the thermal resistance or R-value and is the element's resistance to heat-flow through the materials' given thickness and can be estimated by dividing the depth of the material (d, in metre) by the material's conductivity (k, W/mK). For a construction element with several layers, the individual component's thermal resistances need to be summed. The thermal transmittance or a U-value is the reciprocal of the total thermal resistance (R_t) and is calculated from the thermal resistances of each part of the construction element and is expressed as *"the rate of heat-flow in Watts through 1m^2 of a structure when there is a temperature difference across the structure of 1 degree K or °C*" (McMullan, 2002) and includes surface resistances of the boundary layers (R_{Si} and R_{Se}, m^{2}KW^{-1}) - see *Equation 1*. Surface resistances take into account radiative and convective processes which "*bring heat from the room interior to the inner surface of the construction and remove it at the exterior surface*" (Davies, 1993). Hence a floor U-value expresses convective and radiative heat-flows from the room air and room surfaces to the floor surface and conductive heat-flow from the floor surface to the ground and outside.

$U = \frac{1}{R_t} = \frac{1}{R_{Si} + R_1 + R_2 + \ldots + R_3 + R_{Se}}$ - *Equation 1.*, where R_1, R_2, R_3 are the individual material's thermal resistances in a multi-layered construction and where R_{Si} and R_{Se} are the internal and external surface thermal resistances respectively and where in each case the surface thermal resistance,

$R_s = \frac{1}{h_c + h_r}$ - *Equation 2.*, where h_c is the convective surface coefficient and h_r ($Wm^{-2}K^{-1}$) is the radiative surface coefficient ($Wm^{-2}K^{-1}$ (Szokolay, 2008) and are defined as equations below:

$h_c = h_{ci} = 0.7$ $Wm^{-2}K^{-1}$ for downward heat flow, where internal surfaces or external surfaces which are next to a well-ventilated layer; at external surfaces: $h_c = h_{ce} = 4 + 4v$ (*Equation 3.)*, where v is the windspeed (m/s) next to the external surface (BSI, 2007).

$h_r = \varepsilon h_{r0}$ - *Equation 4.*, where ε is the emissivity and is typically 0.9 for internal and external surfaces (BSI, 2007); and h_{r0} is the radiative coefficient for a black body and

$h_{r0} = 4\sigma T_m^3$ - *Equation 5.*, where σ is the Stefan-Boltzmann constant (= 5.67 $\times 10^{-8}$ Wm^{-2} K^{-4}) and T_m is the *"mean thermodynamic temperature of the surface and its surroundings"* (BSI, 2007).

Ground floor U-values are mainly influenced by the floor's exposed perimeter to the whole floor area ratio (CIBSE, 2015), the ground conductivity and characteristics, foundation and floor wall thickness (and conductivity), surface resistances and any insulation. Heat loss in suspended ground floors additionally depends on a fluctuating void ventilation rate (Anderson, 1991a, Harris, 1997).

Conductive heat-flow (Q_c) occurs within a body or bodies in direct contact and energy flows from the warmer to the colder side,[1] proportional to the temperature difference and the cross-sectional area of the body (Fourier's Law), see *Equation 6.* Natural convective heat-flows (Q_{cv}) occur between a solid body and liquids or gases due to thermal buoyancy (Szokolay, 2008, Hagentoft, 2001)(see *Equation 7. to Equation 8.)*; for example when warm air rises to replace cold air and in turn cooler air replaces the displaced warmer air.

[1] Second law of Thermodynamics governs that heat transfers from warm to cold.

$Q_c = \sum(UA)\Delta T$ - *Equation 6.,* where Q_c is the conductive heat-flow (W), U is the U-value ($Wm^{-2}K^{-1}$), A is the surface area (m) and ΔT is the temperature difference between inside and outside.

$Q_{cv} = Ah_c\Delta T$ - *Equation 7.,* where Q_{cv} is the convective heat-flow (W) and where h_c is the convection coefficient and depends on air velocity, direction of heat flow and surfaces; typically h_c= 1.5 $Wm^{-2}K^{-1}$ for down-ward flowing heat (Szokolay, 2008). Where air movement exists, $h_c = 5.8 + 4.1v$ (*Equation 8.)* where v is the air velocity in m/s (Szokolay, 2008).

Forced convection is caused by wind patterns and pressure differences creating a stack effect (Hagentoft, 2001), which is likely to contribute to suspended ground floor heat loss. Both conduction and natural convection heat-flows are directly proportional to ΔT, i.e. the temperature difference between inside and outside. Radiation heat transfer occurs between surfaces not in contact with each other but heat is transferred by infrared radiation and is proportional to the difference between the 4th power of the object's temperature and the 4th power of the object's surrounding temperature (T_o^4 - T_s^4) and depends on surface reflectances, emittances and absorptance (Szokolay, 2008) - see *Equation 9. :*

$Q_r = \varepsilon\sigma(T_o^4 - T_s^4)$ - *Equation 9.,* where Q_r is the radiative heat-flow (W) between two surfaces and where ε is the emissivity and is typically 0.9 for internal and external surfaces (SI, 2007) and σ is the Stefan-Boltzmann constant (= 5.67×10^{-8} Wm^{-2} K^{-4}) (see also previous definitions) and T_o is the temperature of the object and T_s the temperature of the surroundings.[2]

2.2.1. Solid ground floors

Heat-flow to and from a solid ground floor slab, which is in direct contact with the ground, depends on the temperature difference between the internal and external environment (BSI, 2009b, Hagentoft, 2001, Hagentoft and Blomberg, 2000), and also on seasonal external and ground temperature changes, dwelling heating regime and presence of insulation on the floor and foundation walls. External temperatures influence the ground temperature and this depends on the ground's characteristics, which can have wide-ranging moisture content, thermal capacity and thermal conductivities (Davies, 1993, Rees, 2001) and hence leads to a wide range of ground floor U-values (Harris, 1997). Solid ground floor heat-flow is also a function of exposed floor perimeter (*P*) to floor area ratio (*A*).

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[2] For q (heat-flux density, Wm^{-2}), divide Q (heat-flux, W) by A (i.e. area, m^2)

This is because a location on the floor further away from the external environment will have increased thermal resistance: in the centre of the floor, "*the ground itself adds to the insulation*" while at the building edge *"the path of the heat flow has to curve through the ground back to the outside air"* (McMullan, 2002) due to the geometry of the slab/wall junction. Thus solid ground floor heat-flow is generally increased along the edges and smaller in the centre of the floor (Davies, 1993, CIBSE, 2015), although Spooner's (1982) in-situ heat-flux measurements on solid ground floors did not verify this. Furthermore, the range of heat-flow reduces as floors are insulated (Anderson, 1991b), while the edge effect reduces as external (foundation) walls are insulated (Harris, 1997). A warm ground region sits underneath perimeter foundations, though it is affected by ground surface temperatures further away (Hagentoft, 2001), whereas under the ground slab, temperatures are relatively warm and stable in winter and summer (Thomas, 1999). As such (Spooner, 1982) suggests the use of ground temperatures at 1 metre deep for in-situ U-value estimation for solid ground floors, though this is usually impractical.

The solid ground floor U-value model is set out in ISO-13370 (BSI, 2009b) and in equations below and indicates inclusion of radiative and convective heat-flow components through surface thermal resistances.

$U_g = \frac{2\lambda_g}{\pi B' + d_t} \ln\left(\frac{\pi B'}{d_t} + 1\right)$ - *Equation 10.,* where U is the U-value of the uninsulated or slightly insulated solid ground floor (see ISO-13370 for well insulated ground floor slabs), where λ_g is the soil conductivity (which for clay equals to 1.5$Wm^{-1}K^{-1}$); B' is the '*characteristic dimension of the floor*' and is the floor area (A) divided by half the exposed floor perimeter (P) ($B'=A/0.5P$). d_t is *'the total equivalent thickness of the ground' (m)* (BSI, 2009b) of the solid ground slab and is as per *Equation 11.:*

$d_t = d_w + \lambda_g(R_{Si} + R_f + R_{Se})$ - *Equation 11.*, where d_w is the foundation wall thickness; R_{Si} is the internal surface resistance of the floor and R_{Se} is the external surface resistance of the external ground surface (see Section 2.2.); typical values as per (BSI, 2007); R_f is the resistance of floor slab itself, including the insulation.

2.2.2. Suspended ground floors

Suspended ground floors are not in contact with the ground but have a sub-floor void which is an additional thermal resistance, though this might be offset by the sub-floor ventilation (forced convection), which is an additional heat loss path (Anderson, 1991a). Increased void ventilation leads to increased heat-flow (Harris, 1997), however Anderson (1991a) estimates that U-values do not differ much from solid ground floors with "*typical ventilation rates*" for suspended ground floors (based on void ventilation area opening assumptions between 0.0030 and 0.0015 m/m^2 and 1 to 2 m/s ground windspeed). But it is unknown how representative these assumptions are in actual houses. Furthermore, natural convective heat-flow is considered to be of minimal influence due to *"thermal buoyancy effects favouring upward flow of air and heat"* (Harris, 1997), though it is unknown if this would be the case throughout the void as it is likely to depend on positioning of airbricks for example. Similar to solid ground floors, suspended ground floor thermal transmittances are influenced by heat-flow through the exposed floor perimeter (*P*) as a proportion of the floor area (*A*)(McMullan, 2002); Chapman (1985b) confirmed the presence of an edge-heat loss effect based on a thermographic survey. For suspended ground floors the main heat-transfer mechanisms are illustrated by *Figure 3.* and are:

a., b. & c. conductive heat-flow from floor surface, foundation walls and sleeper walls[3] to the void: dependent on floor finish, joist and wall depths and material conductivities and presence of insulation. Foundation wall heat-flow contributes to edge effects with increased heat-transfer along the perimeter compared to the non-perimeter zone. Also associated convective and radiant heat-flows to surrounding surfaces.

d. natural convection from the void floor surface to the void air; this is temperature difference driven but this component is likely to be small (Harris, 1997).

e. radiation heat-flows to colder void surfaces and the soil/ground surface: radiation heat-flow from warmer floor and wall surfaces to colder void surfaces, including the ground surface (and vice versa).

f. Heat-flow from the ground to the outside: dependent on soil characteristics and soil thermal mass; can be reverse depending on season.

g. cross ventilation (forced convection) in the sub-floor void: forced convection (i.e. wind driven airflow in the void) leads to increased heat-flow from surfaces to the void and external environment. Likely to depend on vicinity to the airbricks, external wind-speeds and void obstructions to void airflow - see Chapter 4 and Chapter 5.

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[3] Also called dwarf walls

h. stack airflow (forced convection) through the floor: i.e. air-infiltration driven by the air temperature/pressure difference between the void and internal environment: depending on gaps and cracks in the floor surface, cooler void air is drawn into the internal spaces and often to outside, increasing heat loss - see Section 2.2.2.1.

i. surface thermal resistances: likely affected by void airflow (Harris, 1994) (not on *Figure 3.)*

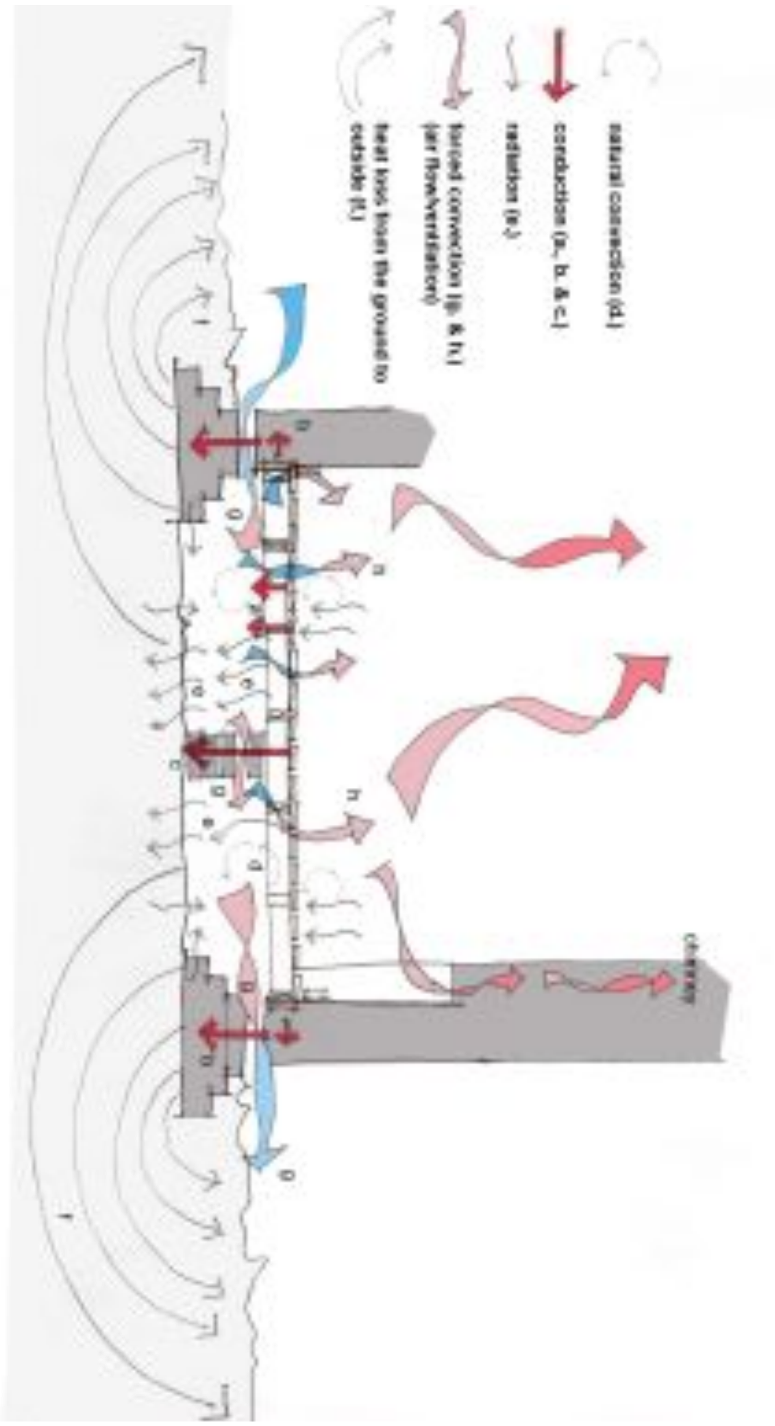

Figure 3. Suspended ground floor heat loss factors; numbers refer to numbers in the text above. In the void, the heat-loss mechanisms are conductive, radiative and ventilative, figure after Harris (1997).

All of the above mechanisms interact; e.g. increased forced convection (g. and h.) in the void might lead to increased heat-flow (Harris, 1994) and there might be colder floor, wall and ground surfaces (affecting radiative heat-flow) and additional heat-flow from thermal bridges (e.g. joists in foundation walls) depending on the detail.

Air-infiltration from the floor void into the internal spaces (h.) has been described as a form of 'heat-recovery' (Miles-Shenton, 2011); i.e. heat lost to the void would to some extent 'pre-heat' the floor-void air before it infiltrates the living spaces above through gaps and cracks in the floor. This 'heat-recovery' mechanism will depend on the total dwelling airtightness and floor airtightness as well as exposure of the void air to the external environment and is likely to vary with fluctuating external conditions, void ventilation rate and in different floor locations. In addition, any recovered air will still be colder than internal room temperature and depending on the airflow velocity and temperature, may contribute to occupant thermal discomfort, with possible associated energy compensating behaviour by occupants.
Any such 'heat-recovery' will depend on ventilation rate and where the void air is being dissipated to and might not lead to any direct heat-recovery into habitable spaces when void air is dissipated to for example floor or wall gaps which are connected to the roof, as observed by Hartless (1994) and Hartless (1996) - see Section 2.2.2. Void air infiltrating in habitable spaces can also affect occupant health - see Section 2.7.

Any uninsulated hot water or heating radiator pipes in the void would act as an additional heat source and would locally condition the void (and might change radiative heat transfer), affecting heat-transfer. Both the presence of such services and the heat recovery effect were excluded in this thesis research but have been highlighted for future research.

2.2.2.1. Floor void air flow and stack-effect

It is unknown what the seasonal pressure differential ranges are between the external environment and indoor spaces and crawl spaces in the UK and how weather and the size, number and location of ventilation openings and other variables affect the pressure differences of the dwelling itself and the floor void. However, according to Hill (2005), in winter, due to internal and external temperature differences, there is likely a slight negative (lower) pressure at the bottom of the dwelling and slight positive (higher) pressure at the top compared to outside. This drives warm air out at the top through construction openings and cracks and pulls cold air in from the bottom through for example gaps and cracks in the floor, creating a stack effect (Hill, 2005, Persily, 2009).

"*While the pressures are relatively small (1 to 5 Pascals), they operate twenty-four hours a day, all winter long, and thus can move a lot of air over the course of a winter*" (Hill, 2005). This stack-effect airflow from the sub-floor void into the rest of the dwelling has been observed in research primarily driven by occupant health concerns arising from moisture problems in the floor void (see Section 2.7.) and the presence of hazardous soil gases such as radon, see e.g. Welsh (1995).

Void airflow is affected by external weather conditions, wind-speed and wind direction and whether the airbricks are located in windward or leeward walls. The greater the sub-floor ventilation, the greater the heat-loss from the floor as observed by Harris (1997, 1993) in a test-cell. This effect is caused by void ventilation replacing warmer void air with colder external air and by decreasing the surface thermal resistances and hence increasing heat-flow from the floor and from exposed foundation walls (Harris, 1993).

Furthermore, Hartless (1999, 1994) found that floor void airflow in a BRE test-house was stack dominated and driven by sub-floor and external temperature differences rather than the wind-speed; this was especially the case at night-time. Additionally, air moved via wall cavities to the ceiling and roof. Under certain environmental conditions Hartless (1999, 1994) also observed that the stack-induced sub-floor airflow converted into sub-floor cross-ventilation, for example with an internal/external temperature difference of more than 6ºC, when airbricks were located in windward walls or if the wind-speed was significantly greater than 3.5 m/s on the windward side. It is unknown whether the findings of this single test-house transfer to other dwellings; it is also unclear where the wind-speed was measured; this might be at the 15m high weather station mention in Hartless (1994) (rather than at airbrick height) or at 10m high as used by models - see Section 2.3.

Similar airflow through floorboard gaps and cracks and stack-effect findings were observed by e.g. Lilly (1988), Oldengarm (1988), McGrath (1999, 1996), Basset (1988) and Williamson (2000), though the study variables are significantly different between studies hence direct comparisons are not possible.

Even with filled floorboard gaps and where floors are carpeted or linoleum finished, air leakage is still likely to occur caused by construction and refurbishment practices, occurrence of service penetrations such as electrical wires, radiator pipes and chimneys as well as non-permanent gap filling and seasonal floor movement (Lilly, 1988, Basset, 1988, McGrath et al., 1999, Thorpe, 2010).

The UK Government's Standard Assessment Procedure (SAP), used for building regulation compliance, assumes that buildings built with suspended timber ground floors pre-1975 in England, Wales and Scotland and pre-1977 in Northern Ireland have unsealed suspended timber ground floors (i.e. with gaps and cracks, assumed 0.2 ach^{-1}) and sealed floors after this period with 0.1 ach^{-1} (BRE, 2014). It is unclear whether this reflects actual air leakage into the dwelling and overall contribution to dwelling airtightness. This stack-effect component is difficult to measure in actual dwellings and floors (see Chapter 3.2.) and is also excluded from floor U-value models - see Section 2.3.

2.2.2.2. Impact of void airflow on floor U-values

Harris' (1997) research in a ~9m^2 test-cell found that floor U-values increased by 40% from 0.62 $Wm^{-2}K^{-1}$ to 0.87 $Wm^{-2}K^{-1}$ with increased sub-floor ventilation rates from 0 to 1.5 ach^{-1}. The test-cell was located in a controlled thermal chamber: temperatures were kept constant at 20°C in the test-cell, air-mixed with a fan, and 10°C ±0.5°C in the cold thermal chamber (Harris, 1993, Harris, 1997). The floor surface to the room above was made air-tight, minimising stack-effect airflow into the space above. Several locations on the floor were monitored and an average U-value obtained (Harris, 2013). Ventilation was provided by fans at the airbricks and altered between 0 ach^{-1} to 1.5 ach^{-1} (equivalent to up to 4m/s wind-speed at airbrick height (Harris, 1994)). The upper limit of 4m/s wind-speed at airbrick height appears to be high compared to the average 5m/s suggested UK heating season wind-speed at 10m height (Anderson, 2006, METOFFICE, 2015, RRR, 2015). Hartless (1994) reported sub-floor airflow rates in a test house to be 2 to 8.5 times greater than documented by Harris (1994), while Lilly (1988) observed in another test house around 5 ach^{-1} and Basset (1988) noted air-change rates of 2 to 8 ach^{-1} in New Zealand floors. Comparison between sources and findings is however difficult as the sub-floor voids are different alongside several other different variables (different climate, terrain obstructions as well as different measurement methods). Detailed characterisation of the void-ventilation rates and typical wind-speeds at airbrick height and in floor voids are unknown and might be highly variable due to the factors mentioned above. It is also unclear how representative Harris' test-cell proportions, distance between airbricks, replicated air-change rates, ground conditions and airflows are compared to actual dwellings. The test-cell walls were also insulated and this was the reason why no significant edge-effect was observed (Harris, 1997). However of interest are not the exact U-values estimated or airflows replicated, but Harris' research highlighted that with increased airflow an increased thermal transmittance trend was observed.

In summary, suspended timber ground floor systems are likely to have fluctuating U-values, which are related to the varying airflow through airbricks and other sources of ventilation; increased sub-floor ventilation is expected to lead to increased floor U-values. Airflow was found to fluctuate with external weather conditions, in particular with wind-speed and wind direction and whether the airbricks were located in windward or leeward walls. Heat-flow might also be influenced by stack driven airflow up through the floor, which is affected by the extent of gaps and cracks in the floor and house-cavities connecting to the floor as well as temperature differences between void and outside. Wind-driven void airflow is likely to displace warm void air with colder air, and to reduce both surface temperatures and thermal resistances in the void (thereby changing radiative and conductive heat transfer); stack-effect airflow might also have similar influences on void conditions and associated heat-flow, however this is not characterised at present.

2.2.2.3. Floor finish

Original pre-1919 floors tend to be of pine softwood floorboard construction (Rock, 2013) and were usually (partially) covered; for example with rugs or animal skin; or with natural hessian, linoleum and sometimes thin parquet floor finish (Rock, 2013, Collings, 2008). Floorboards were usually of not very high quality or finish; though sometimes the floor edges in a room were painted dark, or fitted with more expensive parquet floor finish, using easily removable rugs in the middle of the floor (Collings, 2008). A 1981 survey of almost 400 dwellings in Cambridge, which included similar proportions of dwelling age and typology representative of the UK housing stock at the time, found that around 50% of dwellings had suspended timber ground floors, with 70% carpeted finish and just 16% timber floor finish (Hawkes, 1981). No literature was found that identifies the proportion of different floor finishes in the UK's pre-1919 housing stock. Floor finish will effect floor heat loss and has associated thermal comfort implications - see Section 2.5.

2.3. Suspended ground floor U-value models

Thermal resistances are usually calculated in a perpendicular straight line between surfaces of a building construction. In reality however construction build-ups are not homogenous and junctions between elements occur and the heat may not travel in straight lines as a result of this (BSI, 2009b, Anderson, 2006). This 3-dimensionality affects overall heat-flow, yet in most U-value calculations, this effect is considered to be negligible and calculation methods are simplified to 2-dimensional effects.

Several models exist to calculate suspended ground floor U-values and BS-EN-ISO-13370 (BSI, 2009b) sets out internationally agreed procedures for the U-value calculation methods of both solid as well as suspended ground floors and is used as a basis for floor U-value calculations in CIBSE (2015), RdSAP (BRE, 2011) and software models, e.g. PHPP (PHI, 2007) and BuildDesk U (BuildDesk, 2012). Models estimate the U-value of the whole floor and not for specific locations on the floor. ISO-13370 is a simplified example (BSI, 2009b) and does not include some of the heat-loss mechanisms as identified in Section 2.2.2.; the model and issues with excluded and assumed inputs are discussed below.

The ISO-13370 U-value model for suspended floors with void depths <500mm is based on the combined floor U-value 'U' being determined by heat-flow from the internal to the external environment as set out below in Equations 12 to 20 and as illustrated by *Figure 4.*:

- Heat is transferred from the floor surface to the sub-floor void (U_f, see *Equation 14*), and should include point and repeated thermal bridging separately calculated.
- Heat from the sub-floor void is then transferred to the external environment in the following way:
  - through the ground underneath (U_g , see *Equation 15*)
  - through the foundation walls (U_w)
  - and through ventilation of the sub-floor void ($U_{v,}$, see *Equation 18*); U_w and U_v are combined in $U_{x,}$ (see *Equation 17*)(BSI, 2009b, Williamson, 2006a).

For void depths greater than 500mm, the increased void area adds additional thermal resistance to heat-flow (SBSA, 2010) and for the heat-flow component to the ground, additional parameters are included related to perimeter and depth of the basement below external ground level; different calculations apply if heated or unheated basements; such constructions have been excluded in this thesis.

U_f, U_g and U_X are combined in the equations below and are defined as follows:

$\frac{1}{U} = \frac{1}{U_f} + \frac{1}{U_g + U_x}$ *Equation 12.* and $U = \left(\frac{1}{U_f} + \frac{1}{U_g + U_x}\right)^{-1}$ *Equation 13.,* where

$U_f = \frac{1}{R_{Si} + R_f + R_{Se}}$ *Equation 14.,* and where R_{Si} = 0.17 m^2KW^{-1} (BSI, 2007) and is the internal surface resistance of the floor and R_f is the thermal resistance of the floor. Use of R_{Si} on both sides of the floor (i.e. $R_{Se} = R_{Si}$) as the void is considered an internal space (BSI, 2009b)(CIBSE, 2015).

$U_g = \frac{2\lambda_g}{\pi B' + d_g} \ln\left(\frac{\pi B'}{d_g} + 1\right)$ - *Equation 15.*, where λ_g is the soil conductivity which for clay equals to 1.5 $Wm^{-1}K^{-1}$; and *B'* is the '*characteristic dimension of the floor*' and is the floor area (*A*) divided by half the exposed floor perimeter (*P*), i.e. $B'=A/0.5P$; d_g is *'the total equivalent thickness of the ground (m)*' (CIBSE, 2015) and is as per *Equation 16.* below:

$d_g = d_w + \lambda_g(R_{Si} + R_{Ig} + R_{Se})$ - *Equation 16.,* where d_w is the foundation wall thickness; λ_g is the soil conductivity, R_{Si} = 0.17 m^2KW^{-1} (BSI, 2007) and is the internal surface resistance of the floor, R_{Se} is the external surface resistance of the ground (0.04 m^2KW^{-1} (BSI, 2007)) and R_{ig} is the resistance of the floor including insulation between the floor and the ground; taken to be zero if uninsulated.[4]

$U_x = \frac{2h_f U_w}{B'} + U_v$ - *Equation 17.* , where h_f is the height of the top of the floor surface above external ground level, U_w is the thermal transmittance of the foundation wall and U_v is as per *Equation 18.* below:

$U_v = \left(1450 \frac{J}{m^3K}\right)\frac{a v f_w}{B'}$ - *Equation 18.*, where U_v is the thermal transmittance implied by the ventilation flow rate; a is the ventilation opening area (m^2) per exposed perimeter (m), *v* is the average wind-speed (m/s) at 10 metres height and f_w is the windshield factor depending on location and is 0.02 (urban), 0.05 (suburban) or 0.10 (rural) location.

$U_v = \frac{\rho Q_w C_p}{A}$ *where* $Q_w = 0.59 f_w a P v$ (m^3/s) (Equation 19. and Equation 20.); 1450 J/m^3K is derived from the heat capacity of air (C_p= 1000J/kgK) and density of air (ρ = 1.23 kg/m^3), both at 10 °C. (Note: J= W.s)

[4] Note that R_{ig} is correctly noted in CIBSE (2015), but incorrect in ISO-13370 where it is mistakenly annotated as R_f and in ISO-13370 h_f is defined from top of surface to outside floor level; while in CIBSE (2015), from bottom of floor; in this case ISO-13370 has been used.

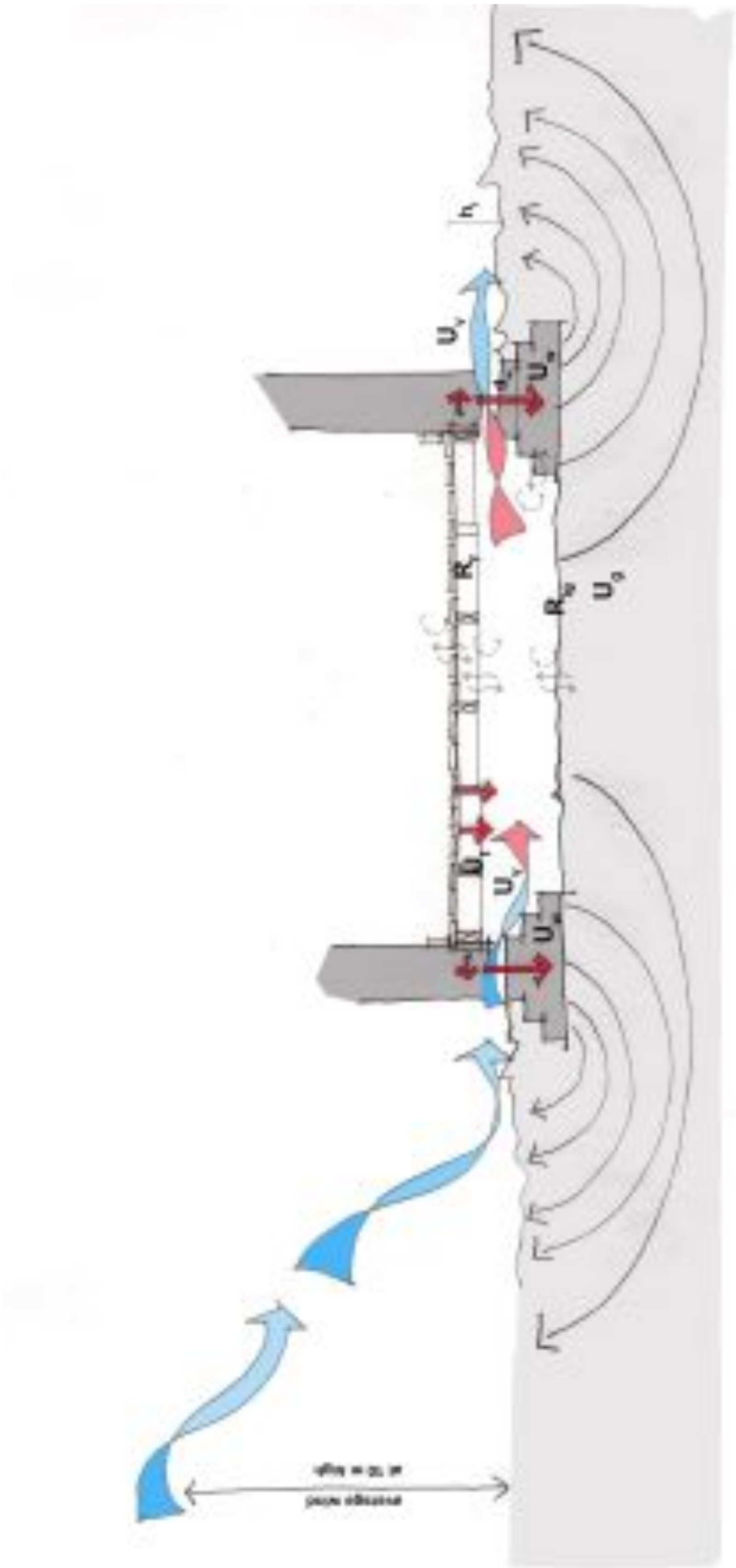

Figure 4. Diagram of heat-flow model of suspended floors after ISO-13370; symbols refer to Equations 12 to 20 and in text; wind-speed in the void is derived from average wind-speeds at 10m height.

The inclusion of surface thermal resistances for the floor structure and the ground in *Equation 14.* and *Equation 16.* respectively includes assumed radiant and natural convection influences at the surfaces in the floor U-value model (as a U-value is air-to-air, not surface-to surface heat-transfer). Likewise for inclusion of U_w in *Equation 17.* as a U-value includes surface resistances. However based on these assumed values, it is unknown whether this accurately represents the convective and radiant heat-flows from air to surface and how accurate these assumptions reflect dynamic conditions even in the same room or floor.

Figure 5. sets out the model's identified assumptions and excluded inputs. Variables excluded from the model include sleeper wall presence, stack-effect forced convection, wind direction and airbrick orientation (windward/leeward sides) and uninsulated service pipes in the void (radiator/hot water pipes). Also excluded is reduced floor void ventilation impact of void obstructions, such as joists and sleeper walls. The model also assumes that the average annual heat-flow, using average annual external and internal temperature differences, is similar to the seasonal heat-flow (CIBSE, 1996, BSI, 2009b); i.e. by considering the heat-transfer over a full year, the impact of thermal mass of the ground is considered negligible (and hence excluded in models). It is not characterised at present whether these exclusions and assumptions might lead to significant inaccurate model outputs or not, nor how this might effect comparison with in-situ measured results - this is subject of discussion in Chapter 5.3.6. Repeated thermal bridges such as joists are not separately accounted for in the ISO-13370 model (BSI, 2009b, BSI, 2009a) and should be included by calculating the proportion of timber joist presence (Anderson, 2006). Linear thermal bridging (such as the wall/floor junctions) are excluded in floor U-value models as they should be included in the whole building's heat loss calculation and not in the separate building element U-value (Anderson, 2006, BSI, 2009b). These can be calculated separately as for example set out in ISO-10211 (BSI, 2009a) or ISO-14683 (BSI, 2008) and as per guidance in Ward (2007).

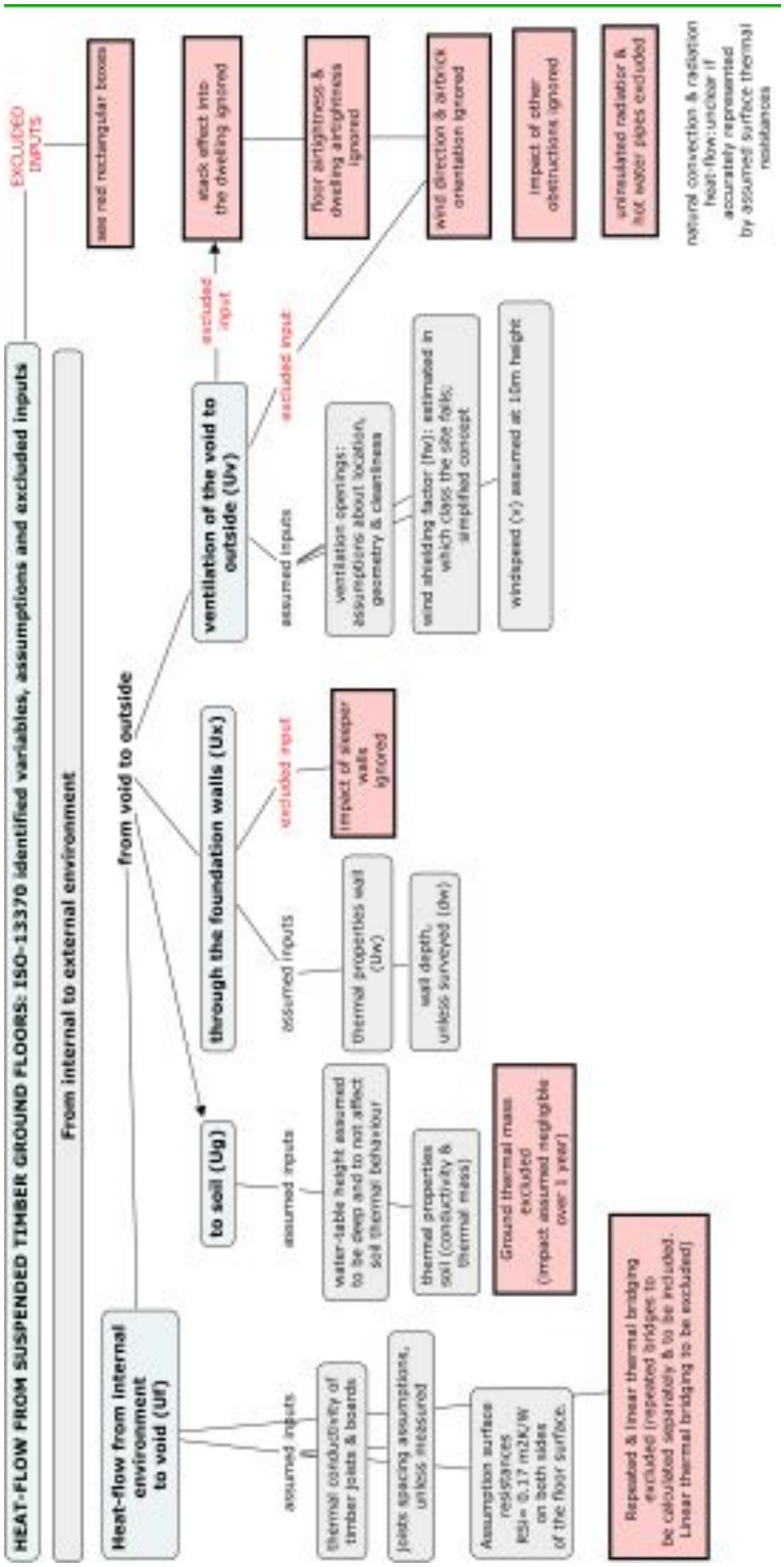

Figure 5. ISO 13370 : summary of model variables (inputs, assumptions and exclusions) - adapted from Pelsmakers (2012)

Reliance on general input assumptions (for example for material conductivities, construction build-up depths, average wind-speeds, airbrick characteristics etc.) might lead to model output uncertainty. For instance Harris (1997, 1993) notes that wrong assumptions about ground conductivity can lead to significantly differently estimated solid ground floor U-values. Other uncertainties include assumptions of a constant ventilation rate through the airbricks (Harris, 1993), assumed wind-shielding factors, assumptions about the effective ventilation area of airbricks (Williamson, 2006a) and assumption of association between 10m high average wind-speeds and those at airbrick height. Furthermore, the model makes no distinction between suspended concrete or suspended timber ground floors and the former's increased floor airtightness. Without a stack-effect component, the model might be more representative of a more airtight concrete suspended floor. This stack-effect airflow might also affect the surface thermal resistances but this is not characterised at present.

Williamson (2006a) critiqued the oversimplification of the model, while Rees (2001), Adjali (2004) and Thomas (1999) have made similar observations for the solid concrete ground floor model. Williamson (2006a) proposed adjustments to U_v to better reflect that (a.) airbricks will block over time (and suggests a 70% effective area), (b.) adjusted wind shielding factors (f_w) and (c.) better averaging of pressure coefficients of the wall to low level airbricks. Williamson's (2006) adjustments are expressed in *Equation 21.* and overall slightly increases the wind driven component (U_v), especially in suburban and in rural locations from increased wind shielding factors (f_w), but it has a small overall impact on the final derived U-value. Williamson's formula is based on a 3 metre building roof height, in itself a limitation.

$U_v = \left(1033\frac{J}{m^3K}\right)\frac{\alpha v f_{w'}}{B'}$ - *Equation 21.*, where U_v is according to Williamson (2006a) as per *Equation 18.* but $f_{w'}$ is the adjusted wind shielding factor 0.03 (urban) 0.10 (suburban) or 0.18 (rural) for a building with roof at 3m height.

For additional detail on assumptions and excluded inputs, see *Appendix 2.A.* It is unknown if (and by how much) the model U-value outputs are affected by the individual or cumulative effect of assumptions and exclusions, nor what their contributory extent to the floor U-value is, all of which are poorly characterised at present.

2.3.1. CIBSE 1986 model

The CIBSE (1986) suspended ground floor U-value model is briefly presented here, even though it is superseded by the ISO-13370 model which is now the basis for the models in CIBSE (2015) and its previous version (CIBSE, 2006). While the CIBSE-1986 model is no longer in use, it is included here for comparison to current models - see Chapters 4 and 5. The model is graphically presented in *Figure 6*. and is described by *Equations 22 to 35*.

The CIBSE-1986 model describes the suspended ground floor heat-transfer as resistances in series and in parallel (see *Figure 6., diagram b)*, and includes thermal resistances for the floor, the ground and a ventilative component alongside radiant and convective components. However some of its limitations include assumptions of ground thermal properties and of the convective (h_c) and radiant coefficients (h_r); a smaller heat capacity of air and R_{Si} of 0.14 m^2KW^{-1} compared to 0.17 m^2KW^{-1} in ISO-13370. For R_{Si} and h_c, the assumed values are based on <0.1 m/s airflow at the surface but this is uncharacterised for the ventilated void. Additionally, it is unknown at which height wind-speeds are to be derived; 1m/s is recommended in CIBSE (1986) which might imply a low-level wind-speed near the building, however this is unspecified. Furthermore, the use of breadth (b) and length (l_f) is limiting for more complex floor plates which are not square or rectangular; there is also an assumption that the free airbrick ventilation area is associated with the longer wall dimension (l_f) rather than the exposed building perimeter. Foundation wall thickness is assumed to be 0.3m with the thermal resistance of the floor (R_g) assumed to be 0.2 m^2KW^{-1} - though a more complex equation (*Equation 34*) can be used to adjust for specific cases. A brief sensitivity analysis and comparison between the current ISO-13370 and superseded CIBSE-1986 model outputs is presented and discussed in Chapter 4.4.3.1.

$$U = \frac{1}{R_t}$$ - *Equation 22.*, where R_t is as per *Equation 23.* below:

$$R_t = R_{Si} + R_g + R_{t1} + \left(\frac{1}{R_{t1} + R_e} + \frac{1}{R_{t2} + R_v}\right)^{-1}$$ - *Equation 23.*, after CIBSE (1986), where R_{Si} is the internal surface thermal resistance, to be taken as 0.14 m^2KW^{-1}; R_g is the resistance of the floor slab (to be taken as 0.2 m^2KW^{-1} (CIBSE, 1986) or $R_g = R_{Si} + R_f + R_{Se}$ (*Equation 24.*); R_{t1} and R_{t2} are derived from *Equation 25.* and *Equation 26.*; R_e is the thermal resistance of the earth and as per *Equation 29.;* R_v is the ventilation resistance and as per *Equation 30.*

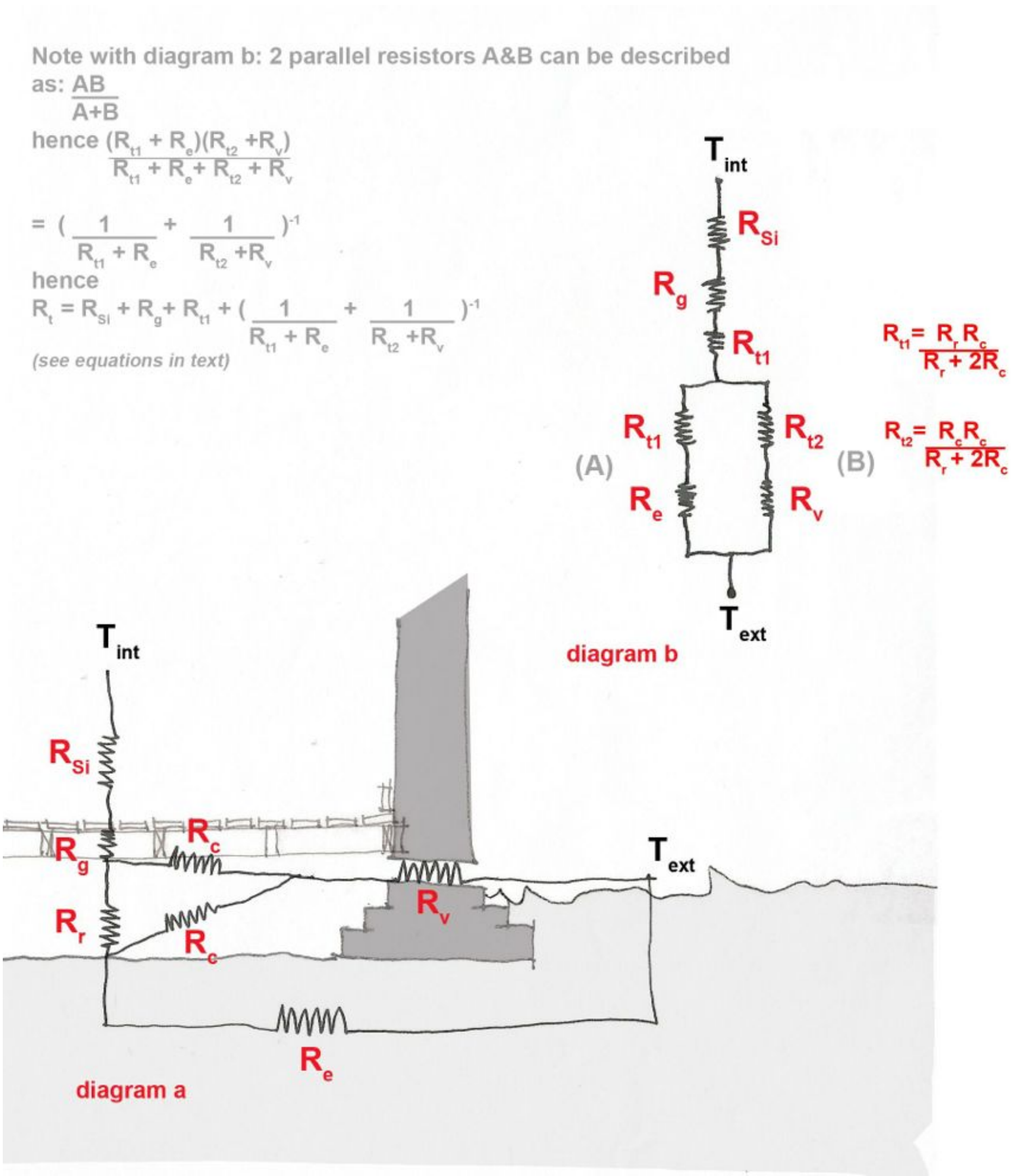

Figure 6. after CIBSE (1986) and adapted from Williamson (2006a); resistance to heat is in series from the internal space to the floor and in two parallel paths from the void to the outside. R_e includes a foundation wall resistance in Equation 34. Letters refer to equations 22 to 35.

$R_{t1} = \frac{R_r R_c}{R_r + 2R_c}$ *(Equation 25.)* and $R_{t2} = \frac{R_c^2}{R_r + 2R_c}$ (*Equation 26*), where R_c and R_r are the resistances from the convective and radiative components as per *Equation 27.* and *Equation 28.* respectively:

$R_c = \frac{1}{h_c}$ - *Equation 27.*, where h_c is the convective heat transfer coefficient to be taken as 1.5Wm^{-2}K^{-1} for downward heat-flow (CIBSE, 1986).

$R_r = (\varepsilon h_r)^{-1}$ - *Equation 28.,* where ε is the emissivity factor to be taken as 0.9 and h_r is the radiative heat transfer coefficient, to be taken as 5.7Wm^{-2}K^{-1} (CIBSE, 1986).

$R_e = \frac{1}{U_g} - R_{Si}$ - *Equation 29.,* where U_g is derived from a table in CIBSE (1986) and assumes that the earth has the same conductivity as a solid ground floor slab with limited prescribed proportions (l_f and b). Alternatively for more specific cases, U_g can be derived as per *Equation 34.*

$R_v = \frac{A_f}{V_f C_v}$ - *Equation 30.,* where R_v is the ventilation resistance in the suspended floor; A_f is the floor area (m^2), c_v is the heat capacity of air (to be taken as 1200 J/m^{3}K (CIBSE, 1986) and V_f is the ventilation rate in m^3/s of the suspended floor, and as per *Equation 31.*

$V_f = 0.66 a v l_f \quad (m^3/s)$ - *Equation 31.,* where a is the airbrick ventilation free opening area per metre length l_f (assumed 0.002 m^2/m (CIBSE, 1986) and v is the wind velocity in m/s; l_f is the long dimension. Hence $R_v = \frac{1.5b}{C_v a v}$ *(Equation 32.*, where b is the breadth or shorter floor dimension; assuming the above inputs with a wind velocity of 1m/s (CIBSE, 1986), $R_v = 0.63b$ (*Equation 33).*

$U_g = \frac{2\lambda_e B}{0.5b\pi} \operatorname{artanh}\left(\frac{0.5b}{0.5b + 0.5w}\right)$ - *Equation 34*., where w is the wall thickness (assumed to be 0.3m (CIBSE, 1986), b is the floor width; B is a floor dimension and derived as per *Equation 35.; artanh* is the inverse hyperbolic tangent $\tanh^{-1}$ and where $B = \exp\left(\frac{0.5b}{l_f}\right)$ - *Equation 35.*, where l_f is the floor length.

2.4. Published suspended timber ground floor U-values

This section gives an overview of published U-values, both calculated and in-situ measured and compares the different sources and highlights issues associated with such comparisons.

2.4.1. Literature floor U-values

The majority of published suspended ground floor U-values are based on industry literature and on an exposed perimeter to floor area ratio (*P/A*). This *P/A* ratio differs depending on building geometry; hence *Table 1.* and *Table 2.* present results separately for terraced houses (assumed *P/A*=0.3) and semi-detached houses (assumed *P/A* =0.6, (Thorpe, 2010)) respectively. Un-insulated suspended ground floor published U-values range from 0.45 $Wm^{-2}K^{-1}$ to 0.70 $Wm^{-2}K^{-1}$ for mid-terraced houses and 0.45 $Wm^{-2}K^{-1}$ to 1.30 $Wm^{-2}K^{-1}$ for semi-detached dwellings; though insufficient information about the variables were provided to establish the cause of the difference between the sources. The average literature U-value for terraced houses is 0.55 $Wm^{-2}K^{-1}$ based on the range of sources in *Table 1.* and 0.77 $Wm^{-2}K^{-1}$ for semi-detached dwellings based on the sources in *Table 2.* Rickaby (2014b) questioned the applicability of *P/A* in a floor with a ventilated void and suggested a doubling of the U-value for uninsulated suspended ground floors from a calculated 0.65 $Wm^{-2}K^{-1}$ to 1.30 $Wm^{-2}K^{-1}$ for a semi-detached dwelling (Rickaby, 2014a, Rickaby, 2014b). The validity of this is unknown and this is likely to depend on the number of airbricks per *P/A* for each dwelling.

There is a difference of 56% between the lowest and highest literature floor U-values for terraced houses and 188% for semi-detached dwellings. While these divergences suggest large differences in literature U-values, these sources are likely to have each used different underlying assumptions and each assumed different dwelling and floor characteristics, which affect the final value. While in some of the literature sources some of the assumed variables are stated, not all literature sources disclose detail of embedded assumptions, such as:

- which calculation model used;
- whether thermal bridging is included;
- material properties and assumptions; (including perimeter wall characteristics, timber conductivities etc.);
- assumed ventilation/airbrick openings;
- exposed perimeter to floor area (*P/A*), which is different between each house typology and also within the same typology;

- soil characteristics; type of soil is only given in SBSA (2010) and CIBSE (2015) published U-values. Even where soil characteristics are stated, this is still based on assumed soil performance, which in turn is based on assumed characteristics such as moisture content.

Source	**Uninsulated floor U-values** $Wm^{-2}K^{-1}$	**Notes**
Mid-terraced house (based on perimeter to floor area ratio (*P/A*) of 0.30, unless stated otherwise)		
BRE(2000)	0.45	No information available; no *P/A* disclosed
Scottish Building Regulations (SBSA, 2010); soil type= clay	0.51	Based on 0.0015 m^2/m ventilation opening (opening area per metre exposed perimeter)
	0.53	Based on 0.0030 m^2/m ventilation opening
CIBSE Guide A (CIBSE, 2015); soil type= clay	0.56	Based on 0.0015 m^2/m ventilation opening
	0.58	Based on 0.0030 m^2/m ventilation opening
EST CE83, 2004 version, p8 (EST, 2004)	0.45-0.70	For mid-terrace and end of terrace; infers these values are for both solid and suspended ground floors. *Note: both lower and upper U-values are included in the average U-value from published literature.*
EST CE83, 2007 version, p9 (EST, 2007, Thorpe, 2010)	0.70	No distinction made between dwelling type. Infers this U-value is the same for solid and suspended ground floors. Thorpe (2010) based U-value on EST CE83, 2007 version (Thorpe, 2013).
EST(2006a) & Griffiths (2007)	0.48	*'Typical un-insulated floor U-value'*: no distinction between solid/suspended ground floor nor house type; no *P/A* disclosed nor ventilation opening assumptions.

Table 1. Published U-values of un-insulated suspended timber ground floors for typical mid-terraced houses with P/A 0.30; adapted from Pelsmakers (2012)

Source	Uninsulated floor U-values $Wm^{-2}K^{-1}$	Notes
Semi-detached house (based on perimeter to floor area ratio of 0.60, unless otherwise stated)		
EST CE83, 2004 (EST, 2004)	0.45-0.70	For mid-terrace and end of terrace; infers these values are the same for both solid and suspended ground floors. *Note: both lower and upper U-values are included in the average U-value from published literature.*
BRE(2000)	0.70	No information available; no *P/A* disclosed
Scottish Building Regulations (SBSA, 2010); soil type= clay	0.72	Based on 0.0015 m^2/m ventilation opening (opening area per metre exposed perimeter)
	0.76	Based on 0.003 m^2/m ventilation opening; soil type= clay
CIBSE Guide A (CIBSE, 2015); soil type= clay	0.79	Based on 0.0015 m^2/m ventilation opening
	0.83	Based on 0.003 m^2/m ventilation opening
Yates(2006)	0.70	Nottingham EcoHome; no *P/A* disclosed nor ventilation opening assumptions
Rickaby(2014a) & Rock(2013)	1.30	Based on a semi-detached dwelling of ground floor plate 6m x 7m (Rickaby, 2014b). *P/A* estimated by author as ~0.45 based on above information. Rock (2013) also approximates an uninsulated suspended timber floor U-value at 1.30Wm^2K^{-1}, however no details or discussion are provided.

Table 2. Published U-values of un-insulated suspended timber ground floors for typical semi-detached houses with P/A 0.60; adapted from Pelsmakers (2012)

The sources with the greatest detail and transparency are SBSA (2010) and CIBSE (2015) which also disclosed they are based on the ISO-13370 U-value model, however this model is also subject to uncertainties as discussed in Section 2.3. The similarity of results for the SBSA (2010) and CIBSE (2015) published U-values (see *Table 1.* and *Table 2.)* could be explained by use of the same theoretical models. Other sources however lack detail and transparency of assumptions, hence comparison between sources is difficult. In addition, no judgement can be made about how representative the published literature U-values may (or may not) be of the actual U-value of a suspended floor and without sufficient detail; such comparisons are unlikely to be robust.

2.4.2. In-situ measured U-values

There are not many in-situ measured U-values for either uninsulated or insulated suspended timber ground floors as also noted by Doran (2008), and not all are recent or for UK floor constructions or climate. A brief consideration of available sources accessible at the time of writing follows below and are listed in *Table 3*. for UK sources.

The largest in-situ heat-flux measuring campaign of suspended ground floors appears to have been undertaken by Isaacs (1985) in New Zealand, who monitored 44 foil insulated suspended ground floors. Some floors were on stilts and thus lacked perimeter walls and were exposed to the external environment, hence internal floor surface to external sub-floor surface temperatures were used in in-situ measurements for practical reasons (without surface resistance adjustments - see Chapter 3.3.). This is unlike other studies and models which measure from the internal to the external environment. Excluding part of the heat-flow path by measuring to the void (such as exclusion of the additional layers of air and the foundation wall and exclusion of the surface thermal resistances) means that the estimated thermal resistances from internal space to void in Isaacs' (1985) study are expected to be lower than if the floor resistances had been estimated to the external environment and if surface thermal resistances had been included, as acknowledged by Isaacs (1985). However, these neglected additional thermal resistances might be small in the exposed floors (i.e. the floors without perimeter walls) (Isaacs, 1985). Measurements were undertaken in single floor locations with large 600mm x 450mm heat-flux sensors so that joist effects could be included; an internal surface temperature sensor was embedded in the heat-flux sensor. Analysis was undertaken by using a cumulative sum to estimate thermal resistances- see Chapter 3.3. Comparison with UK floor constructions is difficult; however Isaacs (1985) found that the mean R-value of the foil insulated sheltered floors - estimated as described above - was 1.1 m^2KW^{-1}, while just 0.55 m^2KW^{-1} for the exposed floors; and the latter generally did not meet prescribed regulations.

Harris (1994, 1997) estimated U-values of a test-cell floor in a controlled environment (as discussed in Section 2.2.2.) Harris' U-value results of 0.62 $Wm^{-2}K^{-1}$ to 0.87 $Wm^{-2}K^{-1}$are within ranges as those discussed from literature sources in the previous Section 2.4.1., though these values are not directly comparable with the published estimated values. Firstly, the main purpose of Harris' (1993, 1997) work was to compare different insulation methods and their performance in certain conditions (Harris, 2013), not to compare measured versus published U-values or other in-situ measured sources.

For example, U-values were calculated from the internal environment to the floor void environment (Harris, 2013), while published and modelled values are based on internal to external environmental conditions. Additionally, the test-cell does not replicate an actual dwelling nor actual field conditions; it had timber insulated walls instead of uninsulated brick walls; reducing edge thermal bridging (Harris, 1997). The P/A is ~1.33m/m^2, which is out of the range of P/A in published literature. Harris (1997) observed U-value reductions of up to 50% depending on insulation method, insulation location and void airflow. Similarly, for an observed point location on the floor, Currie (2013) noted a more significant in-situ measured U-value improvement of around 70% after the floor was insulated - see also Section 2.6 and Chapter 6.

In-situ U-values measured in the field in the UK under real environmental conditions are presented in *Table 3.* and are between 0.69 Wm^{-2}K^{-1}and 2.4 Wm^{-2}K^{-1}, depending whether taken in the middle of the floor or along the floor perimeter and depending on other variables.

In-situ U-values of un-insulated suspended ground floor (point measurements) Wm^{-2}K^{-1}	**Source & Notes**
1.19	Semi-detached house in Derbyshire, ~45m^2 ground floor with part of the floor in solid concrete (Baker, 2011a). Unknown where sensors were placed.
2.4 ±0.2 (perimeter, (Stinson, 2012))	Wells o' Wearie, detached house in Edinburgh, measured at the perimeter (Currie, 2013) from floor surface to external environment with addition of internal surface resistance as per Baker (2011b), confirmed by Stinson (2012). 2.5 ±0.3 Wm^{-2}K^{-1} was obtained when calculated from air at skirting level to external perimeter air temperature (Stinson, 2012).
2.3	Scotstarvit detached Cottage, in Scotland. Unknown where measured on the floor; reference made to use of Baker's (2011) method (Snow, 2012a, Snow, 2012b), which implies internal surface to external environment with addition of an internal surface resistance.
1.19 to 1.93 (perimeter)	Temple Avenue; 1930s semi-detached house. Measured from internal air to external environment; U-value ranges are based on calculated daily averages (Miles-Shenton, 2011).
0.69 to 1.44 (middle floor)	

Table 3. Published in-situ measured U-values of un-insulated suspended timber ground floors; adapted from Pelsmakers (2012).

Comparing the U-values in *Table 3.* with the literature U-values for semi-detached dwellings in *Table 2.,* Section 2.4.1., there appears to be a large divergence between measured and published U-values. Similar divergences were also found by e.g. Baker (2011b), Rye (2010) and Li (2014) for solid walls, where theoretical U-values appeared to over-estimate actual measured U-values. Contrary to this, for the in-situ measured floors listed in *Table 3.,* in-situ measured U-values appear significantly higher than the published sources and those based on theoretical models such as SBSA (2010) and CIBSE (2015). Chapman (1985a) also suggested that floor U-values were significantly higher than predicted. However, direct comparison between these in-situ measured case studies and literature, as well as between the different in-situ sources, is difficult for the following reasons:

- each of the above case studies are subject to different variables: different dwellings of different construction and different terrain obstructions (affecting wind-speeds);

- the in-situ measurements were undertaken on different locations on the floor and were subject to different environmental conditions;

- different sources use different measurement and data analysis methods or did not disclose it; for example U-values were estimated from different internal to external (or void) temperature locations;

- the ISO-13370 model is a whole floor U-value model and not for points on the floor (CIBSE, 2015, Anderson, 2006), while in-situ U-values are spot measurements or point locations on the floor.

Moreover, from physical theory and as noted by Harris (1993), heat-flow is expected to vary across the floor. Increased heat-flow is expected along the edges (perimeter) compared to the non-perimeter zone. This is illustrated to some extent by Miles-Shenton's (2011) in-situ measurements in two point locations, with measurements in one location in the middle of the floor generally lower than those observed in the perimeter location. However, apart from Miles-Shenton (2011), the measurements presented in *Table 3*. are based on single in-situ 'point' U-value estimates. In some sources the in-situ U-value was measured in the perimeter zone, a location of the floor which is unlikely to be representative of the whole floor U-value, and which is expected to be subject to increased heat-flow - see Section 2.2.

This spatial variation of heat-flow might explain large model/literature U-value divergences with in-situ measurements, depending on the floor location where such in-situ measurements were undertaken. Equally, it is unknown whether literature U-values and outputs from ISO-13370 models accurately reflect the actual floor U-value. While the simplification of models allows for quick floor U-value estimates (and generic assumptions negate the need for a detailed survey), model outputs may hence not reflect the actual construction and heat-flow paths due to the previously listed simplifications, assumptions and omissions (see also Section 2.3.). This could lead to over or under-estimation of the actual floor U-value, however the extent of this remains uncharacterised. While some divergence is expected between modelled and in-situ measured values due to input assumptions (BSI, 2014, McMullan, 2002), there are also uncertainties associated with in-situ measurements - see Chapter 3.3.

2.5. Floors and thermal comfort

This section focuses and brings together current research and theory associated with thermal comfort and ground floors specifically. Thermal discomfort is an important factor in dwelling energy use because it might lead to increased energy use to compensate (Rock, 2013) by for example increasing room air temperatures (Olesen, 1979).

Thermal comfort may be defined as *"that condition of mind that expresses satisfaction with the thermal environment"* (ASHRAE, 2013a) and is dependent on the level of personal activity and clothing alongside physiology and psychology and the surrounding environmental conditions (such as humidity, air velocity, air, surface and radiant temperatures) (Olesen, 2000, CIBSE, 2015). Generally thermal comfort theory considers certain local thermal differences of the body to lead to discomforts, such as large differences between head and feet, cold floor surfaces and draughts (Olesen, 1977, CIBSE, 2015, Olesen, 2004, Olesen, 1980).

In many thermal comfort studies, use is made of the Predicted Mean Vote (PMV)(Parsons, 2003), which expresses thermal satisfaction based on the average satisfaction of a large group of individuals, using the ASHRAE thermal sensation scale with 7 values from hot (+3) to cold (-3)(Olesen, 2004). Another index, Predicted Percentage Dissatisfied (PPD) expresses a percentage of thermal dissatisfaction and is derived from people's PMV votes of dissatisfaction with the thermal environment (i.e. votes of ±2 and ±3), assuming a neutral comfort level of PMV = 0 (Olesen, 2004). A PPD of no more than 20% is generally aimed for but often buildings do not provide this for their occupants (Brager et al., 2015). Both indexes relate to the general or whole body thermal (dis)comfort experienced (Olesen, 2004), and not to local thermal discomfort, the latter has particular relevance to uninsulated ground floors.

Limitations of present thermal comfort models are discussed by e.g. de Dear (2011), Parkinson and de Dear (2014) and Arens (2010) and they note that current thermal comfort standards focus on narrow ranges in mostly steady-state environments and are based on the minimisation or elimination of thermal discomfort (negative alliesthesia) rather than on the maximisation of thermal pleasure (positive alliesthesia). Generally predictive thermal comfort theory is developed in controlled environmental thermal labs considering a uniform (steady-state) laboratory environment on whole body thermal comfort.

Less research has been undertaken with transient conditions, changing indoor air-flow, non-uniform environments and impact of cold (or hot) sensations in body parts on overall thermal comfort (and thermal pleasure), when thermal comfort responses become more complex (Zhang, 2009b, Zhang, 2009a, Olesen, 2004, Parkinson and de Dear, 2014). Much research is also based on theoretical behaviour of people, for example the undertaking of light or sedentary activity, wearing of certain clothing at different seasons, when in reality these situations may not occur, or in combination with other factors thermal comfort sensations may significantly differ. For example, an individual might theoretically be considered in whole body thermal discomfort, yet in transient conditions or where occupants have control over their environment or where local heat or cold stimuli are applied, actual overall thermal comfort might be closer to the neutral thermal sensation (Zhang, 2009c) or they might even experience thermal pleasure (positive alliesthesia) (de Dear, 2011, Parkinson and de Dear, 2014).

Main identified thermal comfort theory related to ground floors are mostly local thermal (dis)comfort issues, i.e. where a particular part of a person's body in sedentary or light activity is affected (Olesen, 2000), in this case, the feet. Current thermal comfort theory considers that when someone is exposed to colder conditions, the extremities (head and feet) are also generally colder while the rest of the body is less affected (Munro, 1948). ASHRAE (2013a) Standard 55 considers a 10% PPD margin acceptable for whole body comfort or 5% to 20% depending on different local discomfort factors such as local draughts, vertical temperature differences and cold floor surfaces (Olesen, 2004). ASHRAE (2013a) Standard 55 and BSI (2006) also set out local thermal discomfort thresholds, which, where relevant to ground floors, are discussed below. Thermal comfort theory related to ground floors associates local thermal discomfort with cold/warm floor surface temperatures and air temperature differences between head and feet. According to theory, these local thermal discomfort sensations might also depend on overall room air temperatures; for example when the core body is cold, introducing warmth to a local body part might increase comfort. The reverse might happen when introducing cold to warm body parts, though warming the core body (instead of warming local body parts) might be more effective, as reported by Zhang (2009b).

First, an overview of current thermal discomfort theory from cold floor surfaces is presented, followed by theory on discomfort from vertical air temperature differences in occupied spaces and finally thermal comfort theories related to other local discomfort thresholds are discussed.

Possible discomfort from too cold (or too warm) floor surface temperatures

According to ASHRAE (2013b), when occupants are wearing shoes, it is the floor surface temperature rather than the floor finish which largely determines thermal comfort. Olesen (1977) also found that, over a short period of time and for people with bare feet, the floor temperatures affected local thermal discomfort, which are dependent on the floor's thermal characteristics. Theory recommends floor surface temperatures are between 19ºC and 29ºC (ASHRAE, 2013a, BSI, 2006) and depends on floor finish (Olesen, 1977, CIBSE, 2015), for example on the thermal mass and conductivity of the floor finish. Billington (1948) found that the warmest feeling of a floor is a combination of low thermal capacity and low conductivity (such as cork).

Contrary to this, Munro (1948) claims that overall room temperatures are the main factor in thermal discomfort and that uninsulated floors (or cold floors) in themselves are not the main cause of 'cold' feet. Munro (1948) notes that for individuals with shoes on over a 60 minute period, low air temperatures (< 18ºC) combined with local discomfort caused by a concrete surface (but also linoleum and rubber covered concrete and wood) lead to discomfort. Less discomfort was experienced on cork surfaces, where comfort sensation and feet temperatures were higher than with other surfaces as also found by Billington (1948). As expected, this discomfort is further pronounced with bare feet (Munro, 1948). Nevins (1967) argues that with shoes on, the conducting layer of the floor surface is less important (as the shoe material adds thermal resistance); cold feet might be experienced at floor surfaces ≤15ºC. Heat discomfort was noted by Michaels (1964) at +35ºC floor surface temperatures and with ~24ºC air temperatures. Parkinson (2014) suggests that warm floors might lead to subjects feeling thermal pleasure (positive spatial alliesthesia) despite slightly *"cooler-than-preferred ambient temperatures"*. Brager (2015) describes use of localised foot warmers providing increased thermal comfort at lower room temperatures, reducing overall energy use for space-heating.

Given the many different variables which affect thermal comfort, it is unsurprising that there is little consensus in different sources on the minimum and maximum floor and room air temperature combinations that might lead to thermal (dis)comfort. In summary, suggested comfort floor surface temperature values go as low as 17ºC to 19ºC (ASHRAE, 2013a, BSI, 2006) to as high as 37.8ºC for heated floors (Song, 2008). Likewise, suggested ideal air temperatures range from 20ºC to 24ºC, depending on source (Chrenko, 1957, Olesen, 1977, CIBSE, 2015, ASHRAE, 2013a, BSI, 2006).

Possible discomfort from vertical temperature differences

Olesen's (1979) work was the basis for ASHRAE Standard 55 and BSI-7730 local thermal comfort standards. Discomfort might be experienced when there is a 3°C to 4°C temperature difference between feet (0.1m height) and head (1.1m head height when seated or 1.7 m head height when standing)(ASHRAE, 2013a, BSI, 2006, Olesen, 1979, Parsons, 2003). For standing active people this range might be up to 7°C (Zhang, 2005), but this was based on simulation only. As noted by Parkinson (2014), cooling the head and warming the feet might lead to thermal pleasure.

Other possible local discomfort thresholds

- **Possible discomfort from mean radiant temperature differences between ceiling and floor[5]** might arise if the ceiling is 5°C warmer than the floor, or if the ceiling is 14°C colder than the floor (with room temperatures of 22.5°C), according to ASHRAE (2013a) and BSI (2006). Olesen (1980) suggested that this mean radiant floor/ceiling temperature difference should ideally be less than 4°C to minimise thermal discomfort sensations (for 5% PPD).
- **Possible discomfort from increased airflow/draughts**: according to ASHRAE (2013a) draughts might cause "*unwanted local cooling of the body caused by air movement*" and might particularly affect head/neck/shoulder region and leg region, including feet and ankles. Thermal discomfort from draughts might be most pronounced where room air temperatures are low: ASHRAE (2013a) suggests that draughts should not be greater than 0.15 m/s below 22.5°C to minimise discomfort. CIBSE (2015) suggests a draught airflow increase from 0.1m/s to 0.6m/s might raise the thermal comfort temperature value by 2 degrees.

In the different sources, there is little consensus on the minimum and maximum thermal comfort thresholds; this is unsurprising given the differences of the impacting variables, i.e. differences in physiology, activity and practices (such as clothing levels) and the difficulty in undertaking such studies. However, an in-depth thermal comfort study and impact of discomfort on compensating energy use or on occupant thermal comfort is not within the remit of this research; instead preliminary data is presented and compared with the theoretical ASHRAE and BSI-7730 thresholds in Chapter 6.5.

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[5] Also referred to as 'asymmetric thermal radiation'.

2.6. Floor insulation

Shorrock (2005) estimated that there are nearly 10 million uninsulated suspended ground floors in the UK and Power (2008) argues that floor insulation is essential alongside other fabric intervention measures to achieve significant overall dwelling energy reductions. About 8000 floors were recently insulated under the ECO and the Green Deal policies, though this represents only a small proportion of overall measures - see Chapter 1.2.3. However, no literature was found that identifies the proportion of insulated floors in the UK's pre-1919 housing stock.

Insulating floors might provide many benefits, including reduced energy use and energy bills with reduced associated carbon emissions (Power, 2008), though this depends on space-heating fuels used. An additional benefit of floor insulation might be increased dwelling airtightness as well as better occupant thermal comfort - see Chapter 6.5. EST (2006b) suggests that up to 60% heat loss reductions might be achieved by insulating suspended timber ground floors. Floor insulation was also highlighted as a cost-effective carbon reduction measure by Shorrock (2005), Rickaby (2014a) and Mackenzie (2010), with estimated carbon reductions of 1.82 million tonnes of CO_2 per year for the UK housing stock, excluding any compensating occupant behaviour such as 'take back'[6](Mackenzie, 2010). It is unclear what these estimates are based on and estimated carbon reductions will be lower when low carbon space-heating supply increases.

However, some dwelling retrofits estimated significant energy reductions without insulating floors by using higher fabric standards elsewhere, for example 'Cottage Retrofit' at the Isle of Wight (TSB, 2012). Furthermore, Friedman (2014) found that floor insulation was, together with doors, one of the least considered energy efficiency upgrades to conservation properties from a sample of 116 industry respondents. Forty one percent said improving floors was not a major objective; while only 9% to 18% said it was considered in most if not all projects respectively (Friedman, 2014).

[6] The 'temperature take back factor' is "*the degree to which fabric and ventilation changes could result in increases in indoor temperature as opposed to lower energy consumption.*" (Hamilton et al, 2011)

The upgrade of existing ground floor structures is regulated by Building Regulations Part L1B, which recommends insulated floor U-values of maximum 0.25 $Wm^{-2}K^{-1}$ for the entire floor when at least 50% of the floor surface is upgraded or replaced or where 25% of the entire building envelope is renovated (NBS, 2015). Exceptions exist for listed buildings and other relaxations exist to take account of practical and technical constraints (such as maximum 15 year payback, difficult floor level differences between parts, structural issues). In these cases a maximum U-value of 0.70 $Wm^{-2}K^{-1}$ is allowed (NBS, 2015). New ground floors are to be built to the same maximum U-value of 0.25 $Wm^{-2}K^{-1}$ in England and Northern Ireland and maximum 0.18 $Wm^{-2}K^{-1}$ in Scotland and Wales. These are improvements from 0.45 $Wm^{-2}K^{-1}$ in 1990, prior to which no recommendations were specified for floors (Dowson et al., 2012).

Other sources also recommend upgrade of floors with maximum U-values of 0.20 to 0.25 $Wm^{-2}K^{-1}$ (for example EST (2004, 2007)); Rickaby (2014a) recommends 0.25 $Wm^{-2}K^{-1}$ as good practice and 0.15 $Wm^{-2}K^{-1}$ for advanced practice. Such advanced U-values of 0.16 $Wm^{-2}K^{-1}$ and 0.13 $Wm^{-2}K^{-1}$ are reported by Baeli (2013) for the Shaftesbury Park Terrace with fully-filled floor void with EPS beads (p37) and for Midmoor Road (p 41-42) respectively. The latter design value was achieved with a combination of 100 mm rigid insulation on top of joists and 100 mm mineral wool insulation between the joists. In another case study in Brent, spray foam floor insulation was predicted to lead to a U-value of 0.12 $Wm^{-2}K^{-1}$ but no further information was provided regarding the material or application depth (Baeli, 2013, p 65-66).

Large thermal improvements were also predicted for replacement of suspended timber ground floors with an insulated concrete ground floor: for example in Hawthorn Road, a U-value of 0.12 $Wm^{-2}K^{-1}$ was predicted with 200 mm EPS on top of a new concrete floor (Baeli, 2013, p 46), and 0.13 $Wm^{-2}K^{-1}$ in Greenwich (LEB, 2011a). In Liverpool, a U-value of 0.12 $Wm^{-2}K^{-1}$ was estimated by rebuilding a suspended ground floor with a proprietary product called Supafloor (LEB, 2011b).

The above floor U-values are based on modelled design predictions, not on actual in-situ measured performance, of which there are only a few published. Currie (2013) reported a 70% U-value reduction from 2.4 to 0.7 $Wm^{-2}K^{-1}$ in one pre-post measured point U-value; the floor was insulated with 80 mm woodfibre between joists. Harris (1997, 1994) observed up to 50% heat-flow reduction by insulating a test-cell floor and by stapling a radiant barrier under the joists of a test-cell; increased void airflow reduced the U-value reduction achieved. In New Zealand, Cox-Smith (2008) investigated the performance of foil insulation over time and observed that newer reflective foil draped over joists performed slightly better than when draped under joists and when soiled after several years. Isaacs (1985) conducted large-scale in-situ heat-flux monitoring of 63 houses in New Zealand and observed that foil-insulated floors with enclosed floor voids generally met the (then) stipulated building standards, while floors with no perimeter walls (i.e. exposed to the outside) and foil insulation did not meet those standards.

While insulation of floors should lead to reduced heat loss and increased space-heating energy savings, it might also lead to increased moisture build-up as found by Airaksinen (2003) in Finland. Airaksinen (2003) observed that floors with a typical U-value of 0.2 $Wm^{-2}K^{-1}$ had average void relative humidity (RH) almost 10% higher than floors with U-values of 0.4 $Wm^{-2}K^{-1}$; the latter floors lead to 2°C warmer void air temperatures on average - see Section 2.7. Despite slow uptake of floor insulation, thousands of floors have already been insulated - see Chapter 1.2.3.; yet the impact on heat loss reductions, occupant thermal comfort and on floor void conditions are unknown, which hinders informed retrofit decision-making.

2.6.1. Typical floor insulation methods

In the UK typically a fibrous insulation is installed in between joists (*Figure 7*. option a) (BRE, 2000, EST, 2005, EH, 2010, Rock, 2013). Insulating floors with limited void access, such as the floors subject of this thesis, usually requires lifting of the floorboards, which is a disruptive process (Rickaby, 2014a). Access to floors from below is less disruptive (Roberts, 2008) though not always possible due to health and safety concerns. Despite potential large carbon savings (Shorrock, 2005), the disruptive potential of full floor insulation might lead to little uptake according to Dowson (2012), Shorrock (2005) and Killip (2011), who argue that full floor insulation in between joists makes only sense when taking up the floorboards anyway.

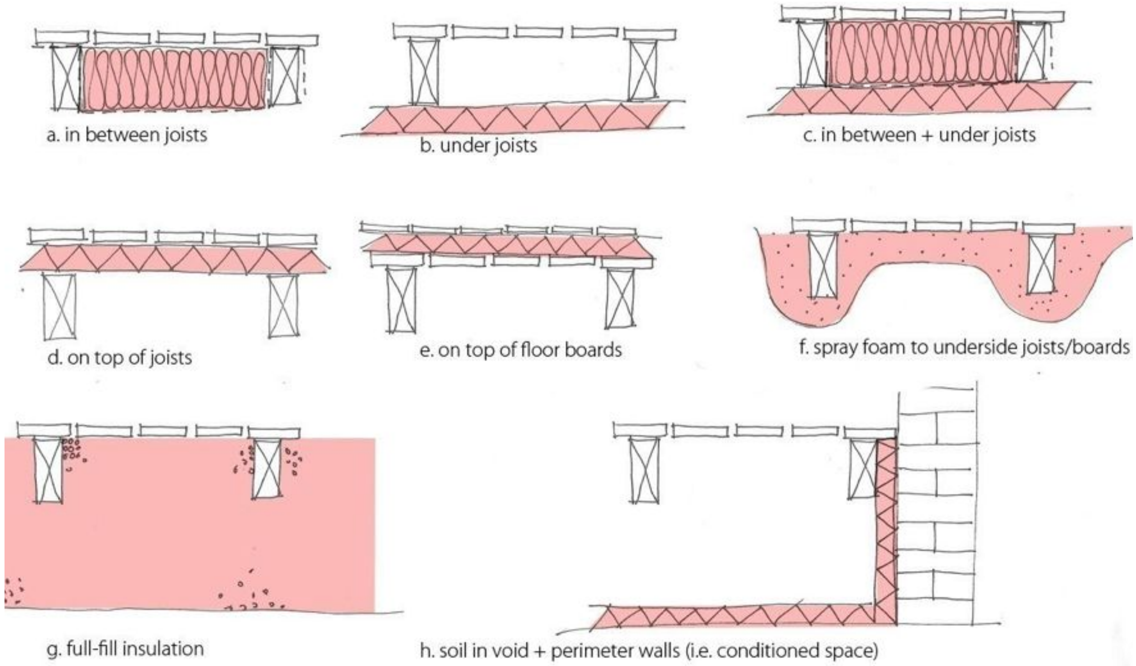

Figure 7. Typical floor insulation methods identified, including typical floor insulation installed in between joists (a.), under joists (b.) or a combination of insulation in between and under the joists (c.), on top of joists (d.) or on top of the floor boards (e.). Other methods include insulation sprayed to the underside of the floor boards and/or joists (f.), full-filling the floor void with insulation (g.) and installing insulation on the ground in the void and/or on the foundation perimeter walls (h.).

Little is published on insulation methods in terms of heat-loss reduction, thermal comfort improvements or any unintended consequences. There are several fixing options and combinations, usually aiming to improve airtightness with vapour permeable membranes at the underside of joists or with radiant barriers; sometimes membranes are also placed directly on top of the joists, or in both locations (see *Figure 7.)*. The effect of insulation on dwelling airtightness is discussed in Chapter 6.5. Placing insulation on top of the joists reduces the joist thermal bridging effect but is more disruptive (Harris, 1997), and door openings, skirting boards and electrical sockets need adjusting (see *Figure 7.d* and *e)*.

Some novel insulation methods have recently been tested, most focusing on insulating the floor by lifting the fewest floorboards, thereby minimising disruption and intervention times. For example, Retrovive (2015) blow cellulose fibre into a breather-membrane strategically installed by lifting only specific floorboards (Collings, 2015, Retrovive, 2015). Some systems include full-fill EPS bead insulation (*Figure 7.g*), as was undertaken at Shaftesbury Park Terrace (Baeli, 2013, TSB, 2011).

To avoid beads spilling out and to reduce moisture being brought in from the outside, airbricks are permanently sealed, though this is considered controversial as it is assumed airbricks regulate moisture in the void (see Douglas (1998c), BRE (1991) and Singh (1998)) and as discussed in Section 2.7.2.). The long-term impact of sealing airbricks in general or of these EPS bead-filled floor voids are however unknown.

Other innovative methods include remote spraying of insulation in floor voids (Baeli, 2013, p 65-66) (*Figure 7. f*), allowing simultaneous encapsulation of the joists, which otherwise tend to remain uninsulated and become a thermal bridge after insulating between the joists. Q-bot (2015) are trialling robotics to survey the floor and apply insulation in this manner[7] (Lipinski, 2015) while U-Floor Technologies, developed by Sustainable Venture Development in London, is a new innovative device deployed through the airbricks and using a natural, sprayable insulation material (Czako, 2015).[8]

The different installation options can be achieved with different insulation materials, some of which are listed in *Appendix 2.B*. Insulating timber floors is likely to increase the floor's thermal mass: typically the thermal mass of an uninsulated suspended floor is between 5-7 kJ/m^{2}K (carpet/vinyl floor finish on floorboards respectively; excluding foundation walls and the ground); which can increase to 17-19 kJ/m^{2}K with 100 mm mineral wool in between the joists (CIBSE, 2015, table 3.53). This is however, still a relatively small thermal mass compared to solid concrete floors (38-58 kJ/m^{2}K carpet/vinyl, uninsulated)(CIBSE, 2015) and the presence of the soil underneath the floor (1285 kJ/m^{2}K based on 1 metre depth of common earth (CIBSE, 2015, table 3.37). Thermal mass is important in moderating temperature fluctuations and shifts temperature variations. Hence material conductivity, thermal mass and time constant (i.e. the time it takes to respond after a change) are important material characteristics to consider in relation to heat-loss reduction interventions.

Generally, insulating floors reduces the heat-flow from the internally heated spaces to the floor void (and hence to the external environment) and the sub-floor void air and surfaces will become colder and closer in temperature to the external environment. This in turn affects the thermal mass equilibrium of the ground and foundation walls and the moisture content of the sub-floor void might increase to critical moisture levels for mould growth in summer - see the following Section 2.7.

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[7] The author was involved with q-bot for early research design in 2013/2014, based on the research design tested and developed in this PhD research to support q-bot in thermal performance monitoring, however no pre-post data was shared for analysis to be included in the thesis at the time of writing.
[8] The author and the innovators signed a mutual NDA and confidentiality agreement.

2.7. Unintended consequences of insulating floors

Insulating floors might lead to unintended consequences, such as moisture build-up in floor voids as found in some other countries. This can lead to fungal growth and timber rot, affecting occupant health in the spaces above and leading to possible structural damage. However, there is absence of UK evidence at present. Other consequences might be increased fire risk if old electrical wires are embedded, risk of burst water pipes (EH, 2010) and radon build-up (Lugg, 1997) - see *Figure 10, page 87*. However these latter issues are not subject of this PhD research. This section gives a brief overview of possible causes of moisture build-up in the floor void, the role of airbrick ventilation and regulatory requirements and why moisture build-up might be a problem and what the identified issues are with insulating floors. Little UK research exists in this area, hence research is drawn together from non-UK sources, though it is unknown to which extent overseas findings transfer to pre-1919 suspended timber ground floor constructions in the UK climate.

2.7.1. Causes of moisture build-up in suspended ground floors

There is an increased risk of damp and mould problems in pre-1919 dwellings (DCLG, 2010) with around 5.8% of floors requiring repair of some kind (DCLG, 2010). Moisture problems have also been reported in suspended floors since the 1940s in the USA (Rose, 1994b). Moisture build-up in pre-1919 suspended floors can be caused by several different variables; the main identified causes are summarised below and illustrated by *Figure 8.* (letters below relate to *Figure 8.*).

Moisture from the ground (A): wet soil (because of high ground water level) or standing water in the floor void could cause high evaporation rates and high RH in the void, which can transfer to the indoor spaces above (Harris, 1995). Where no ground cover exists, as likely the case in most existing old suspended floors (Douglas, 1998c), evaporation from damp soil is considered a major source of moisture (Harris, 1995, Moses, 1954). Evaporation depends on differences in moisture content between crawl space air and ground, void ventilation and the thermal behaviour of the ground (Kurnitski, 2001); Building Regulations require ground-covers (NBS, 2013), which were also found to be effective in avoiding moisture build-up in existing floors (Harris, 1995, Rose, 1994a, Flynn, 1994, Brook, 1994, Stiles, 1994). Joists supported by brick walls can become damp where timber joists are in contact with soil (Tsongas, 1994) or due to rising damp (or driving rain or 'splash back'), especially a risk without damp proof membranes (Harris, 1995, Oliver, 1997, Douglas, 1998b, Ridout, 2001, Tsongas, 1994).

Lack of external site drainage and/or if the external ground level is above the floor (B) so that water can enter floor voids (Rose, 1994b, Brook, 1994, Oliver, 1997, Singh, 1998).

Leaks from services (C) above/below the floor or leaks from rainwater runoff pipes nearby (Brook, 1994, Tsongas, 1994, Morton, 2013), though spillage from living spaces above is probably rare (Harris, 1995) and as with leaks are likely to be localised (Douglas, 1998b).

Impermeable floor finishes (D): BRE (1991) notes some risk from impermeable floor finishes preventing moisture evaporation to the spaces above where previously this was possible and may tip wood moisture content above what is desirable. Insulation material characteristics are also important - see *Appendix 2.B.*

Ventilation: moisture brought in from the outside through airbricks and other non-airtight paths (E): see discussion in following Section 2.7.2.

Increased floor insulation (F) leads to colder void air and surface temperatures, impacting on void moisture conditions (Samuelson, 1994, Airaksinen, 2003). In Finland, Airaksinen (2003) observed that floors with a typical U-value of 0.2 $Wm^{-2}K^{-1}$ had average void RH almost 10% higher than floors with 0.4 $Wm^{-2}K^{-1}$ U-value; the latter floors lead to 2°C warmer void air temperatures on average. Section 2.7.5. sets out a separate discussion of the risk of insulating floors. See also *Appendix 2.D.*

Surface condensation (G) can occur when the void air reaches its moisture vapour saturation point at a given temperature and condenses against surfaces in the void which are below the dew point temperature[9] (Moses, 1954). This is likely to be rare in insulated floors in winter (Harris, 1995); but this might occur especially in summer when warm, humid air meets for example cold, uninsulated metal pipes or other cold surfaces as found by Lstiburek (2008) and Hill (2005) in the USA. No UK evidence for this was found as part of this research.

Some possible solutions to floor void moisture management include: ground covers, ground insulation, mechanical void ventilation when void conditions reach critical levels and reduced floor insulation to increase downward heat-flow, leading to reduced void RH (Airaksinen, 2003, Samuelson, 1994) - see more detail in *Appendix 2.D.*

[9] dew point is the saturation temperature at which the air is 100% RH

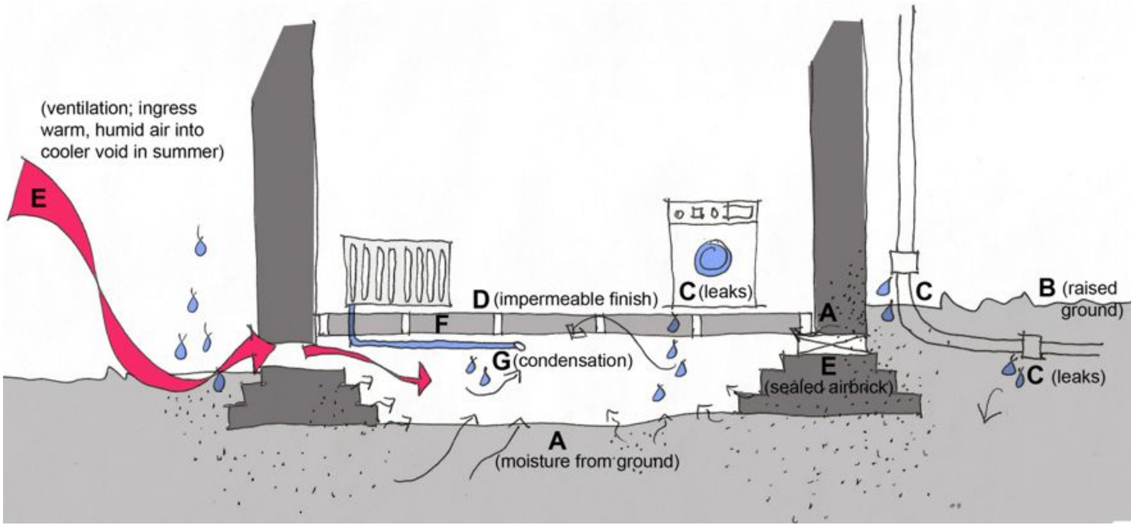

Figure 8. illustrates possible causes of moisture in pre-1919 suspended timber ground floors; letters refer to letters in text above.

2.7.2. The role of airbricks and ventilation in the void

Houses were generally built with floorboards directly placed on bare ground (Muthesius, 1984). After 1860, floorboards were no longer placed directly on bare ground, but had to be suspended on joists, with airbricks ventilating the floor void (Cook, 2009, Muthesius, 1984); a 150mm minimum ventilation zone below the timber floor joists was required to avoid rotting of the timber ground floor structure (Muthesius, 1984). This requirement exists to today in the UK Building Regulations (NBS, 2013).

Pre-1937 floors are unlikely to have damp-proof membranes (Douglas, 1997, Douglas, 1998c). In the UK, Part C (2013) provides guidance for moisture in new ground floors and are required to be built with damp-proof courses protecting the timbers and usually a 100mm concrete over-site ground cover to resist ground moisture, with the top of the over-site concrete above external ground level. Alongside the 150mm minimum ventilated zone below the joists, a requirement exists for ventilation openings: 0.0015m^2 per metre exposed wall perimeter, or 500mm^2/m^2 of floor area, whichever is the greatest (NBS, 2013). When insulating floors, these ventilation requirements also apply (NBS, 2015).

However BRE (1998) notes that existing floors often have less than the current minimum recommended ventilation areas. Yet existing floors with no over-site concrete might need 0.0030m^2/m ventilation opening area[10] (BRE, 1998, Douglas and Singh, 1995); this is also the default assumption in the (Rd)SAP floor U-value model (BRE, 2014) and was until the early 1970s also the requirement in Scotland (Douglas, 1998a). It is however unclear what these standards are based on and if indeed such standards are sufficient to prevent timber rot, or whether they are overly cautious. Suspended floor void ventilation requirements appear to have been developed ad-hoc (Harris, 1995) rather than evidence based, as also noted by Williamson (2006b) for floor ventilation requirements in other countries.

According to Hill (2005), winter void ventilation is generally via stack-effect up through the floor into the internal spaces (see Section 2.2.2.1.), hence the void might be kept dry. Furthermore, in winter, due to heat-flow from the spaces above, the uninsulated floor void is generally warmer than external conditions and incoming external cold air is warmed up and the relative humidity (RH) reduces (Kurnitski, 2001). Typically in summer, warm, humid air enters the generally cooler floor void thereby increasing RH, exacerbated by the high thermal mass of the ground and walls: the warm summer air might be insufficient to increase the air and surface temperatures of the floor (and hence reduce void RH) (Kurnitski, 2001, Airaksinen, 2003, Rose, 1994b, Hill, 2005, Samuelson, 1994). This might lead to summer surface condensation in the void or to moisture build-up (high RH), leading to optimal mould-growth conditions.

Hill, (2005) suggests that ventilation on its own might be insufficient to deal with significant amounts of moisture build-up in floor voids and Douglas (1995) acknowledges that even when voids are well ventilated, humidity can build up in void recesses. While increased void ventilation might also increase the swift dispersal of moisture build-up (Kurnitski, 2001) especially in winter (Hill, 2005), this may not always be effective (Harris, 1995). Furthermore, increased void ventilation leads to an increased evaporation rate from damp soil/surfaces which might increase moisture build-up in the floor void (Harris, 1995). Increased void ventilation also leads to increased floor heat-flow as described in Section 2.2.2.2. A balance between floor void 'health' and heat loss is hence important.

[10] Typically 0.0030 m^2/m is one airbrick per exposed perimeter and 0.0015 is one airbrick per 2 metres perimeter , according to Anderson (1991a).

Sealing airbricks

Clearly, outdoor air cannot dry the floor void if it infiltrates at a higher moisture content than the floor void itself and instead will bring moisture in; hence Kurnitski (2001) argues that if there is no moisture source in the void (i.e. if the void is 'moisture insulated') there is no need to ventilate but acknowledges that *"any leakage in the moisture insulation can bring about high relative humidity"* (Kurnitski, 2001). However, Part C of the Building Regulations (NBS, 2013) and industry guidance for the insulation of suspended timber ground floors suggest that obstructing or reducing floor void ventilation can lead to build-up of moisture in the floor void (Rickaby, 2014a, EST, 2006a, BRE, 2000). Lack of void ventilation and/or sealing of airbricks is considered by many to be the cause of moisture build-up in floor voids (Oliver, 1997, Burke, n.d., Douglas, 1998c, Douglas, 1998a, BRE, 1991, Singh, 1998).

Contrary to this, a sealed void is reported by others to prevent moisture build-up risk in summer (Rose, 1994b, Samuelson, 1994, Lstiburek, 2004), though Kurnitski (2001) points out the difficulty associated with sealing airbricks to control summer moisture ingress because air can enter via other ventilation paths.

These latter observations are based on non-UK climates and constructions; while in the UK, Oliver (1997) notes the importance of unblocking any sealed airbricks in summer. Reduced void ventilation can occur when (partially) blocking airbricks with insulating material, whether intentionally (such as when filling the floor void with insulation - see Chapter 6.3.1), or unintentionally. Note that sealing of airbricks is considered undesirable when radon is present (Welsh, 1995, Lugg, 1997), however this discussion is excluded for the purpose of this PhD research.

2.7.3. Implications of moisture build-up in the floor void

The main danger of moisture build-up in floor voids is that it can lead to fungal growth and timber decay (Moses, 1954, Singh, 1998, Oliver, 1997). However, there is little information about the prevalence of mould growth and timber rot in existing pre-1919 UK dwellings. Few records of such manifestations appear to exist; though it was reported that from 1945 to 1949, 12.3% of housing repairs around Paddington were primarily for dry rot, affecting around 2,400 properties (Frankland, 1951). It is unknown whether this occurred in floors or other construction elements. Most occupants do not realise the presence of fungal growth or timber decay until some incident indicates its presence (Frankland, 1951), such as fine red dust (caused by dry rot spores) on floor surfaces (Morton, 2013, Ridout, 2001) or springy floors (Singh, 1998) or failure of floorboards or floor joists (BRE, 1998).

However, occupant health might be affected prior to any visual manifestation of a problem as contaminants (such as fungal spores, microbes and bacteria which can thrive in moist environments) can be transferred from the floor void air flowing into living spaces above as noted by Frankland (1951), Kroger (2007), Airaksinen (2004, 2003) and (Coulter, n.d.). Dampness and mould exacerbate asthmatic conditions (Frankland, 1951, WHO, 2009) and fungal spores are associated with respiratory problems (Park et al., 2004, Verdier et al., 2014). Moist environments can also give rise to the production of MVOCs (Microbial Volatile Organic Compounds) by fungal and microbic organisms (Paavilainen, n.d.) which can also effect human health (Korpi et al., 2009, Fiedler et al., 2001). As such the transfer of air from contaminated floor voids into internal spaces is a significant concern for occupant health (Airaksinen, 2007). All airborne spores can be a health hazard but in all cases remedy and prevention of moisture build-up and water penetration eventually kills the fungus (Ridout, 2001, Oliver, 1997) and reduces occupant exposure.

Much work on contaminant transfer from floor voids into internal spaces above is based on Finnish apartments which are continuously mechanically ventilated, creating an airflow from the floor void into the de-pressurised indoor spaces above (Airaksinen, 2003). In the UK, Victorian houses typically do not have continuous mechanical ventilation and this phenomena might be less prevalent but is uncharacterised at present. Nevertheless, stack-effect driven airflow from void to internal spaces and cavities above was observed in naturally ventilated dwellings (see Section 2.2.2.). This winter stack-effect acts as a drying mechanism of the floor void (Hill, 2005) and is less pronounced in summer and if buildings are air-conditioned, the opposite effect can occur in summer, with indoor air infiltrating in the void spaces (Hill, 2005).

Infiltration depends on airtightness, building characteristics and internal/external temperature differences and weather effects (wind) (Sherman, 1987). Seasonal temperature conditions lead to different pressure differences between void and internal spaces; spores are more likely to infiltrate in winter due to the stack-effect, however floor void contaminants might be lower during the winter season (though Kroger (2007) reported concentrations of microbes in floor voids to be higher in winter than in summer). The main risk to occupant health appears to be during summer, when floor void conditions are more favourable to mould growth but when this stack-driven infiltration is less dominant. Nevertheless, wind-driven infiltration from the void is likely to find its way into internal spaces (Hartless, 1994) in summer, enabling the spread of fungal spores in living spaces above - see *Figure 9*.

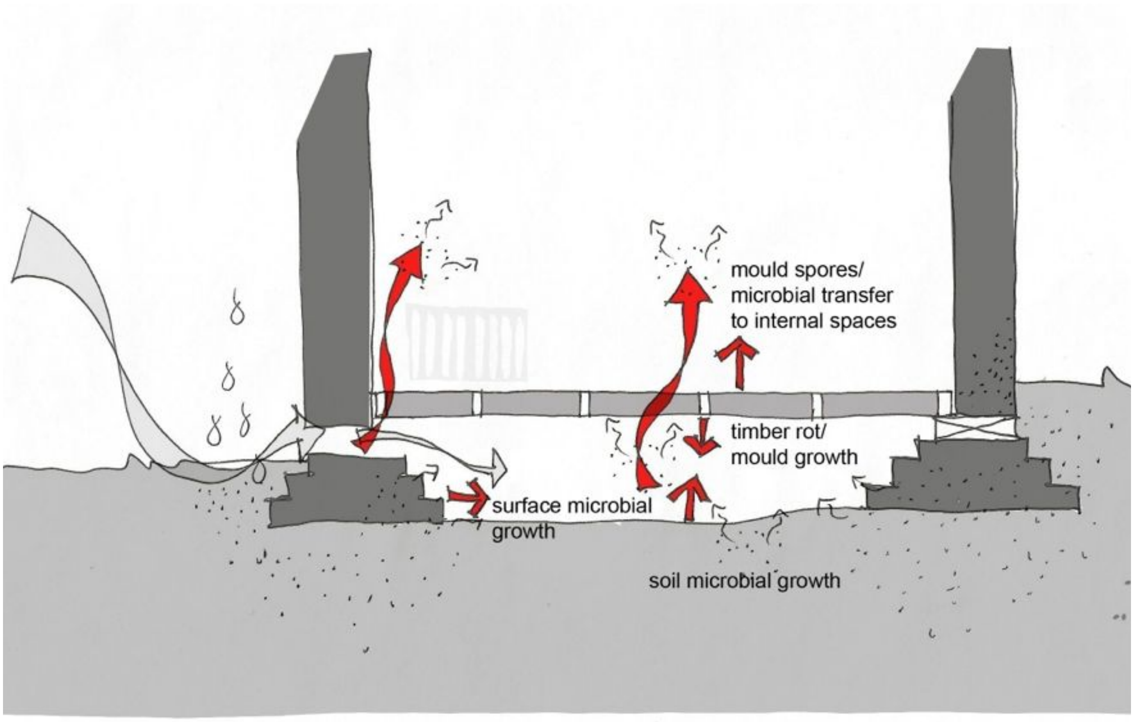

Figure 9. Sources of mould and microbial growth could transfer to internal spaces - diagram adapted from Airaksinen (2003).

2.7.4. Mould growth thresholds

The main occurring organisms in floor voids are wood rotting fungi (such as dry rot and wet rot) and non-wood rotting fungi, which either grow on timber or on other materials and can lead to mould growth (Oliver, 1997). Mould growth tends to occur at lower moisture thresholds (see *Appendix 2.C.)* and is a precursor of wood-rotting fungi, which require higher moisture requirements. Hence setting the thresholds for floor void conditions based on mould growth contamination has the benefit of reduced moisture build-up risk and therefore also reduced risk from structural damage from timber decay. Mould growth risk has also been used by most research in this area to evaluate a construction's condition, such as seminal work by Airaksinen (2003) for Finnish floor voids and Hukka (1999), Viitanen (2010), Sedlbauer (n.d.) and Johansson (2012) for other internal construction elements.

The strongest drivers for mould growth are a combination of relative humidity, temperature and exposure time (Sedlbauer, n.d., Paavilainen, n.d.). Of minor importance are other factors such as PH-value, oxygen and light availability (Sedlbauer, n.d.). Material substrate also plays a role; timber is the building substrate with the lowest threshold for mould and fungal growth. Hence conditions inhibiting mould and fungal growth on wood should inhibit it on other substrates.

Wood can have a high Wood Moisture Content (WMC) if directly in touch with wet surfaces, but also if in floor voids with high RH: timber as a hygroscopic material will absorb moisture from the atmosphere until in equilibrium with the surrounding air (Ridout, 2001). Generally timber decay fungi (such as wet and dry rot) require ≥95% RH (or 28-30% WMC, (EH, 2010)) and temperatures of 0ºC to 45ºC; while mould growth can occur with RH of ≥75% in a similar temperature range - see *Appendix 2.C.* Timber decay does not generally occur below 22-24% WMC, often lowered to 20% as a safety measure (Ridout, 2001) (or equivalent to around 90% RH (EH, 2010)) and is ideally below 15% WMC (Ridout, 2001) (or <75% RH (EH, 2010)). At very high RH (> 97% RH or wet materials) bacteria also cause smell and health problems similar to mould fungi (Viitanen et al., 2010). Fungi usually require stable, unchanging environments to thrive in and are therefore often limited to the damp zone (Ridout, 2001).

However, high RH for a short duration "*will not lead to fungal growth if the periods at low humidity preventing mold [sic] growth are long enough*" (Viitanen et al., 2010). Generally the lower the temperature, the higher the RH usually for mould growth to develop (Oreszczyn, 1999); lower temperatures are likely in floor voids in winter due to external airflow exposure. Even in dry conditions, mould can grow on wet and nutrient rich surfaces and in colder conditions of 10°C, which are less ideal for fungal growth so growth occurs slowly but could "*accumulate considerably during years and decades in the life of a building*" (Pasanen, 1991), but this is poorly characterised for floor voids.

In the UK, Building Regulations Part F determine critical RH thresholds and durations for buildings, but these are based on typical indoor conditions (NBS, 2010), while floor void environments are likely characterised by lower air and surface temperatures and seasonally different RH conditions and with greater fluctuations than might be typical for indoor conditions. *Table 4.* presents critical RH and temperature mould growth thresholds over time from different sources; note most of these are from controlled laboratory studies of specific fungi and on specific substrates.

Temperature threshold	**RH threshold (%) (i.e. critical RH)**	**Time to mould growth of several sources** (average days)	**Source**
5°C	80%	n/a	Hukka (1999)
5-25°C	78% - 95%	42+	Nielsen (2004)
10°C	75% - 95%	7+	Johansson (2012)
10-17°C	80%	60	Pasanen (2001)
15-23°C	80% - 97%	8+	Sedlbauer (n.d.)
20°C	90%	38	Isaksson (2010)
20°C	58% - 97%	1+	Vereecken (2012)

Table 4. Summary table of different estimated mould growth thresholds for less hazardous moulds on timber substrates. Time to mould growth depends on source and combination of temperature and RH threshold and extent of mould growth (i.e. whether microscopic or visually present).

Predicting mould growth is complicated by the fact that the in-situ factors affecting growth fluctuate with the weather and the season and localised effects may not be representative of the rest of the construction (Oreszczyn, 1999). The need for longitudinal measurements of temperature and RH to assess risk of fungal growth is emphasised by Pasanen (2001) and Airaksinen (2013). As such most mould growth research has been conducted in laboratories to determine the likelihood and extent of different fungal growth under different environmental conditions with different exposure times (Oreszczyn, 1999) and sometimes also under fluctuating conditions. These laboratory studies are also the basis for mould growth prediction models and 'post-processor'[11]models (H. Altamirano-Medina, 2009). However, the big differences between lab and in-situ conditions can make mould growth predictions unreliable and depending on which source or model used, different mould growth risks could be diagnosed (Vereecken and Roels, 2012, Vereecken et al., 2015, H. Altamirano-Medina, 2009). Different models exist, but most are only suitable for interior surfaces, such as ESP-r model, Condensation Targeter II and WUFI-BIO 3.2. (H. Altamirano-Medina, 2009, Oreszczyn, 1999, Fraunhofer, 2015). VTT (The Finnish Technical Research Centre) developed a mathematical research mould growth model, which was used for evaluating Finnish floor voids by Airaksinen (2003) for Scandinavian timbers (Vereecken and Roels, 2012). This model was recently updated and validated with Finnish floor void data (Airaksinen, 2013) but the model was not publicly available at the time of writing and ideally requires year-long seasonal data to evaluate the mould growth risk[12](Airaksinen, 2013, Pasanen, 2001).

2.7.5. Insulating floors and moisture build-up risk

In uninsulated floors in winter, when the void air is warmer than the external air, the external air entering the void is warmed up and its relative humidity (RH) decreases, keeping void spaces dry. In summer, when warmer, humid external air can enter the void mainly through airbricks, this increases the risk of surface condensation as the void air and surfaces are cooler than outside and the void' s thermal mass draws heat from the warm incoming air, further reducing the void air temperature and increasing the void RH. This might lead to more optimal void RH and temperature conditions for mould growth.

[11] 'Post-processor' models are models which evaluate mould growth risk based on actual RH and temperatures collected rather than predictive models which asses a structure's mould growth risk based on modelled temperatures and RH.

[12] Hence this model could therefore not be used for the data collected here. Other research models exist such as BREVENT (Edwards, 1990) and CFD software MOISTURE-EXPERT, developed for a Southern USA climate and floor construction (Karagiozis, 2005). However these were not procurable and required unavailable site-data as input parameters.

Insulating floors reduces the heat-flow to the void, and surfaces and void air are expected to become colder and closer in temperature to the external environment in winter. This in turn affects thermal mass equilibrium of the ground and foundation walls and the moisture content of the sub-floor void might increase to critical moisture levels for mould growth, especially a risk with warm, humid summers (Hukka, 1999, Pasanen, 2001). Ventilation paths are also likely to be altered post-insulation, likely reducing upward airflow from the void through gaps and cracks to the spaces above (Henschel, 1992, Stephen, 1998): as upwards airflow through the floor is reduced, floor void cross-flow becomes more important to whisk away moisture laden air or other sources of moisture to maintain healthy floor voids.

RBKC (n.d.) states that "*the addition of insulation dramatically increases the risk of condensation which could cause structural decay of the floor timbers*", while concern is also expressed by Shrubsole (2014). In the USA, Lstiburek (2008), Hill (2005), Flynn (1994) and Fugler (ASHRAE, 1994) report that insulated floors have moisture issues, in some cases leading to mould growth and wood rot in the US; Coulter (n.d.) reported damp floor voids in Canada. High summer humidities in insulated floor voids are also reported by Burke (n.d.) in Sweden and Werther (2010) in Germany. However the problems caused in the floors investigated by for example Lstiburek (2008) were related to floors located in a climate characterised by hot and humid summers and at increased risk for moisture build-up, further exacerbated by summer surface condensation on uninsulated air-conditioning ducts in the floor voids. In Finland, optimal conditions for fungal growth were reported (Hukka, 1999, Pasanen, 2001, Matilainen, 2003, Kurnitski, 2000), especially with high RH in summer (>80%) , regardless of the ground cover and with temperatures in the floor voids between 10ºC and 17ºC (Pasanen, 2001) - see *Table 5*. As mentioned in Section 2.7.1., Airaksinen (2003) observed better insulated floors (0.2 $Wm^{-2}K^{-1}$) to have a higher void RH then floors with U-values of 0.4 $Wm^{-2}K^{-1}$, which were 2ºC warmer on average in the void, with 10% lower RH. Fungal concentrations were found to be up to ten times higher in the floor void compared to indoor spaces during winter and highest in summer, possibly suggesting more favourable conditions for fungal growth during summer when concentrations outside are also higher (Airaksinen, 2003). With an airtight floor, no fungal spore transfer was found to take place from concrete and EPS or PUR layers in the floor to indoor spaces in lab studies (Viitanen et al., 2010). While there is less air-infiltration through solid concrete floors (and can be negligible depending on construction build-up (Sherman, n.d.)), for timber floors, "*penetration of fungal spores is difficult to control by sealing and by controlling the airtightness of the building envelope*" (Airaksinen, n.d.). Instead, balanced building ventilation with equal air intake and extract might be an effective measure to control spore transfer from void to indoor spaces (Airaksinen, n.d.).

VOID temperature (°C)	**VOID RH (%)**	**Source + notes**
10 to 17°C	**60-95%**	Pasanen (2001), measured May to September; mid-summer highest RH; above 80% RH for 8 weeks.
n/a	**90-95%** summer near foundation walls **60-70%** in winter **80-90%** both summer & winter, ground insulation	Samuelson (1994), insulated floor.
Air Temp: 7-19.5°C **Soil Temp:** 6-18°C	**68%-88%** no ground cover **50%-75%** plastic ground cover	Kurnitski (2000), insulated floor
n/a	**67%-84%** natural ventilation **66%-82%** mechanical ventilation	Kurnitski (2001), insulated floor
Wood house: 1-14°C **Apartment:** 4-22°C	**n/a**	Matilainen (2003); insulated floor; 75% RH maximum considered as safe threshold

Table 5. Summary table of different sources for measured floor void conditions; all based on Scandinavian climate and usually over several seasons; most are based on insulated floor voids. Depending on the combination and duration of void RH and void temperatures, mould growth risk may occur in voids.

Contrary to the above reported floor void moisture accumulation in insulated floors, Harris (1995) and EH (2010) suggest that condensation risk in insulated floors is likely to be minimal. Additionally, Tsongas (1994) reported almost non-existent moisture-related issues in floor voids for a relatively large and varied sample of 121 insulated and uninsulated, ventilated and sealed suspended floors in 5 different locations in the Northwest of the USA. Tsongas (1994) associates this absence of moisture issues with the local climate's dry summers unlike in other regions of the USA. However, most floors in Tsongas' (1994) study were inspected during winter-time when the risk of condensation, moisture build-up and mould growth might be smaller and any evidence of temporary damp joists or mould growth may have dried out after winter void ventilation as described in Section 2.7.2. Nevertheless, evidence of more severe timber decay as reported by Lstiburek (2008) and Flynn (1994) if it had occurred, would have been visible during winter inspections yet were not observed by Tsongas (1994), apart from in a few floors with plumbing leaks or wood in contact with soil.

Whether the floor void conditions reach or exceed critical mould growth thresholds will depend on many variables, including climate, extent and characteristics of floor insulation and dwelling construction, alongside the presence of moisture sources, causes of moisture build-up (Section 2.7.1.) and moisture management solutions (see *Appendix 2.D.*). The dry rot timber decaying fungi require a food source such as timber and calcium, which are present in brick and cement/lime mortar but also in rock or glass wool insulation (Douglas and Singh, 1995), commonly used in buildings (EH, 2010), including floors. EST (2006a) recommends that the floor void is to be inspected for damp and timber rot and should be rectified prior to insulating the floor. Nevertheless, there is little conclusive evidence that insulating suspended floors on its own increases mould growth risk. Given the many variables that influence moisture accumulation, it is unsurprising that several studies reported high moisture build-up in insulated floors, while others reported no issues. *Figure 10*. summarises the possible unintended consequences associated with insulating floors based on international case study evidence.

Furthermore, while physical principles remain the same, it is unclear to which extent these findings transfer to pre-1919 suspended timber ground floor constructions in the UK: the cases described have significantly different climate, floor construction methods/materials and building ventilation/heating and cooling systems. In addition, some condensation risks in the void were associated with cooling ducts in the void, but air-conditioned dwellings in the UK are rare, though could increase in the future (He, 2005, Pathan, 2008).[13] Without characterisation of existing floor void conditions and in the absence of evidence of insulated floor void conditions and increased moisture build-up in the UK, no clear conclusions can be drawn whether similar issues occur in the UK. Similar to suspended timber ground floor heat-flow not being well characterised in-situ, neither are existing hygrothermal floor void conditions, even less so once insulated. While it is beyond the scope of this thesis research to define floor void ventilation requirements and safe moisture thresholds, initial empirical floor void data was collected; the research design of which is set out in Chapter 5.2.3.2. The data collection was restricted in time and other limitations (as described in Chapter 5 and 6) and no pre/post insulation floor void comparisons could be made; significant further research is required.

[13] Cooling ducts in the UK might also be differently designed and installed, such as avoiding running uninsulated cooling ducts through the void.

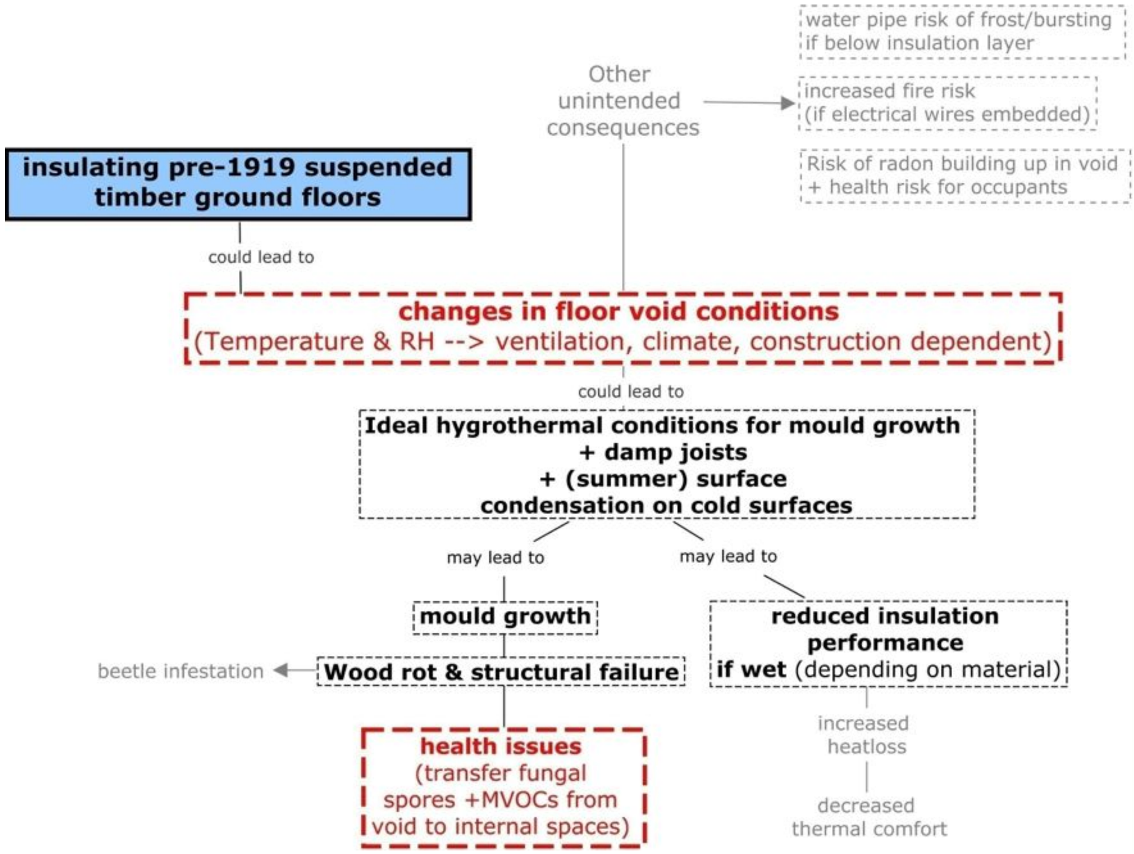

Figure 10. Summary diagram of possible unintended consequences associated with insulating floors, based on international case study evidence; in the absence of UK evidence, it is unclear how this transfers to the UK. Adapted from Pelsmakers (2013).

2.8. Summary

The literature review highlighted several research gaps in the characterisation of floors and floor thermal performance, and highlighted uncertainties and limitations of current research. Of particular note was the lack of in-situ floor heat-flux measurements and difficulty to compare in-situ with published and modelled U-values; different recommendations in policy and in industry could result in different retrofit decision-making, depending on which values are used.

Despite the availability of some interesting results related to floor heat-flow and sub-floor airflow, many of these findings were difficult to directly transfer to the larger UK housing stock due to the fact that the work was either undertaken in test-cells or conducted for different purposes than to estimate and compare floor U-values. Likewise, the overseas research findings have probably limited applicability to pre-1919 UK dwellings due to the differences in climate and building design.

Despite these limitations, certain principles can be transferred more generally, including the complexity of both measuring and modelling floor U-values and the possible factors influencing floor heat loss in pre-1919 UK dwellings. We can expect that suspended timber ground floors are likely to have increased heat-flow along the perimeter and have varying U-values, related to the varying airflow through airbricks. The greater the sub-floor ventilation, the greater the floor heat loss is expected.

The insulation of suspended timber ground floors could potentially provide significant heat-flow reductions as highlighted by Harris (1997) and Currie's (2013) work; this would likely lead to associated energy savings and carbon emission reductions. Multiple options are available in terms of floor insulation (Section 2.6), however the relative merits and limitations of these floor insulation approaches in actual pre-1919 UK dwellings is poorly characterised. Most importantly, the lack of pre/post intervention studies create uncertainty about the actual performance and efficacy of interventions.

While an apparent divergence between in-situ measured and published U-values was found for suspended ground floors, robust comparison between sources was not possible, partly due to the lack of sufficient detail and transparency of both published models but also in-situ measured sources. In addition, where measurements are taken is expected to significantly affect estimated U-values.

Current U-value conventions and tools might be ill-suited to accurately predict the actual U-values of pre-1919 traditional solid walls (Baker, 2011b, Rye, 2010, Gentry, 2010, Zero Carbon Hub, 2010) and this also raises questions about the actual U-values of suspended timber ground floors and the cost-effectiveness and benefits of retrofit measures and highlights the importance of research in this area.

Finally, aside from providing U-value reductions, floor insulation might have other benefits, such as impacting positively on occupant thermal comfort. However, insulating floors might also potentially have a number of unintended consequences, such as changing floor void conditions to become ideal for mould growth, which can impact on occupant health. While some research exists on the effects of void conditions on mould growth and humidity levels, this work has been carried out in constructions and climates outside the UK, and the extent of their generalisibility and transferability to the UK is unknown - see Section 2.7.

2.9. Research questions and objectives

Given the premises outlined above, the work presented in this PhD thesis focuses on testing floor heat-flow theory and testing and refining measuring methods, practices and analysis techniques for uninsulated and insulated floors. Additionally, this research adds original knowledge about uninsulated suspended timber ground floor heat-flow and what the impact of insulating such floors might be, leading to research outcomes that are relevant to industry practice, policy and academia. In particular it aims to answer the following research questions:

1. **How should in-situ suspended timber ground floor U-values be estimated?**
2. **What is the in-situ measured thermal transmittance of floors and how does it compare to model predictions?**
3. **How does the in-situ thermal performance of a case study floor change after intervention measures?**
   - 3.1 *What are the thermal comfort implications of insulated and uninsulated floors?*

The purpose of this PhD research is to test and construct knowledge and understanding of suspended timber ground floor heat-flow and how to measure this heat-flow. The research objectives are three-fold:

- To test, refine and develop research design and analysis methods to estimate the in-situ measured U-value of floors.
- To quantify the in-situ thermal transmittance of some existing floor constructions.
- To quantify the in-situ heat loss reduction potential and thermal comfort implications of some floor interventions.

To meet the above research objectives, the research design takes a multi-method approach for case studies research with some experimental testing, using primarily quantitative methods supported by some qualitative methods such as building and thermographic surveying and visual observations. These methods are discussed, together with research limitations, in Chapter 3 and in more detail in the relevant chapters.

2.10. Definitions

Terms and definitions used in this PhD research are outlined below to clarify how a number of technical terms and definitions are used in the following chapters. Additionally, to allow for comparison purposes between floor model outputs (U-values) and most literature sources (U-values), in-situ measurement results are presented as U-values rather than R-values. Where R-values are stated in literature, R-values will be used.

'Pre-1919 dwellings' and 'pre-1919 floors' are studied and for the purpose of this thesis research include those constructed between 1860 and 1919, excluding the pre-1870 floors without ventilated void spaces, while also excluding basement floors. More recent suspended timber ground floors constructed with cavity walls instead of solid brick walls are excluded, though aspects of this PhD research might be relevant to these constructions.

'Floors' always refers to 'suspended ground floors' unless specifically defined otherwise and by this is meant the whole floor system, i.e. the floor surface including the void, its substructure and the foundation walls and ground to the outside.

Heat loss is used when describing all heat loss mechanisms of the floor, including air-leakage.

'Floor thermal performance' is used as a generic description of all of the heat loss characteristics.

'Floor characterisation' is a generic term used when describing the floor's characteristics, such as void condition, dimensions, heat-flow, thermal comfort etc.

Heat-transfer is the movement of heat by conduction, convection or radiation.

Heat-flux is the rate of heat-transfer (W- Js^{-1})

Heat-flow is the heat-flux density, q (Wm^{-2})

U-value is the thermal transmittance ($Wm^{-2}K^{-1}$) and **'point U-value' ,** also abbreviated by **U_p-value**, is the term used as a generic description of the small area-based in-situ U-value measurement on a certain location on the floor.

'Whole floor U-values' refers to the area-weighted summation of several in-situ point U_p-value measurements (see Chapter 4.4.2.) to allow for comparison with models; models are based on whole floor U-values.

'Floor U-value model' is used primarily to denote mathematical calculations, which attempt to describe steady-state suspended ground floor U-values, and are generally simplified models of the floor system's thermal characteristics. Software models tend to use these mathematical models and calculate a whole floor's U-value.

'Low-resolution' and 'high-resolution' refers to in-situ monitoring in just a few locations on a floor or to many locations on a floor respectively. Given that estimated in-situ U-values are based on small area, or 'point' measurements of a construction element, this differentiation is important: averaging a few 'point' measurements to estimate a whole floor's U-value leads to much greater uncertainty compared to many points being averaged to determine a whole floor U-value - see Chapter 3.3.2 and Chapter 4.4.2

Chapter 3: Research design and methodology

3.1. Introduction

The purpose of this chapter is to give an overview of the research design and research methodology supporting the research questions and objectives identified at the end of the previous chapter (Section 2.9.).

This chapter is split in three parts: the first part presents an overview of the available research methods, with a brief discussion of the benefits and limitations of each method, to give a rationale for the methodological choices in this work. Part 2 presents and critically evaluates measurement protocols available for in-situ U-value data collection, data and error propagation analysis and examining theoretical and practical issues affecting in-situ measuring of floors, which are further described and tested in Chapter 4. The third part presents the testable hypotheses and primary data collected for this thesis and the sampling approach used, discussing the generalisability and the relevant research ethics.

For ease of reference, detailed research design for specific case-studies are set out in the appropriate individual field-work chapters prior to presentation, analysis and discussion of results.

3.2. Part 1: Research methods to investigate suspended timber ground floor heat loss

There are several research methods used to characterise in-situ floor heat loss. These methods include in-situ heat-flux measurements, infrared thermography, co-heating tests, blower door tests and tracer gas techniques. Their advantages and limitations are briefly discussed in the following sections.

3.2.1. In-situ heat-flux measurements

In-situ heat-flux measurements provide an estimated U-value (thus often referred to as in-situ U-value measurements) and this is detailed in Section 3.2.6 and 3.3.

In-situ heat-flux measurements are increasingly used in industry and in academia to evaluate a building element's actual performance, in both new and existing buildings, and to compare in-situ measured to predicted performance, e.g. Li (2014), Rye (2010), Baker (2011b) and Ficco (2015). In-situ heat-flux measurements have been used for suspended timber ground floors only in a limited number of studies. As described in Chapter 2.4., Harris (1997) used multiple heat-flux sensors in a test-cell study; while Currie (2013), Snow (2012) and Baker (2011a) measured single points on a suspended timber ground floor and Miles-Shenton (2011) measured in a few floor locations. In New Zealand, Isaacs (1985b) measured heat-flow at single area locations on suspended ground floors. This research method was also used by several others for solid ground floors, e.g. Trethowen , Delsante (1990) and Thomas (1999, 2009).

These studies however present results from single point-measurements (i.e. at low resolution), with the exception of Harris (1997) and Miles-Shenton (2011); the latter indicated that there is a large variation of floor heat-flow depending on measurement location, based on only a few measuring locations. Similar variation in heat-flow has been observed by a few in-situ studies for solid ground floors, e.g. Delsante (1990). In-situ heat-flux measurements have also been successfully used with one or a few point measurements in pre/post insulation interventions, e.g. Byrne (2013) and Stevens (2013) for walls and by Currie (2013) for pre/post monitoring of one point measurement on a suspended timber ground floor.

Because of how in-situ measurements are taken, they only provide a 'point' measurement of the heat-flux on that location on a given surface under certain conditions over a certain amount of time. Because of the expected variation in heat-flow on a floor, important considerations include sensor placement on surfaces, sensor number and how to devise the best set up to compare to models such as where to measure temperatures. However none of this is well characterised and this is further discussed in Section 3.3. Another limitation is that in-situ measurements on the floor surface in occupied dwellings are disruptive and limit sensor location choice, quantity and monitoring duration. In occupied dwellings, there is also a risk of occupant interference and lack of control over heating patterns, affecting the variables being measured. A sufficient temperature difference between the internal and external environment is generally also required to reduce the relative measurement error, which means that any monitoring using this method should be undertaken during the winter season[1]- see Section 3.3.3.

While in-situ heat-flux measurements measure conductive heat-flow, radiative and convective components influence the observed conductive rate of heat-transfer but these mechanisms cannot be isolated with in-situ heat-flux sensors alone. This research method also excludes other heat loss mechanisms at play, as identified in Chapter 2.2.2., such as heat loss from forced convection and ventilative stack effects.

3.2.2. Infrared thermography

Infrared (IR) thermography helps the understanding of heat loss through construction elements by visually representing surface temperatures (from which heat loss might be inferred) caused by for example construction irregularities or air leakage paths (BSI, 1998) and moisture spots (Grinzato, 1998). While a detailed heat-flow estimate cannot be obtained from a thermographic survey, it can provide insights into the spatial distribution of heat loss and features that may be of interest to study using heat-flux sensors. For this reason, this qualitative method is useful in heat-flux sensor placement (ASTM, 2007a) to help identify any areas of interest for investigation (or exclusion). Given that IR thermography cannot accurately estimate floor heat-flow, it cannot be compared to model outputs.
Similarly to in-situ heat-flux measurements, generally a sufficient temperature difference between the internal and the external environment is required (usually about 10ºC (BSI, 1998, EST, 2006), though might depend on camera specification) and observations are dependent on changing internal and external environmental conditions (Fox, 2012).

[1] This seasonal limitation might be overcome by using Biddulph's (2014) analysis method, though this has not yet been tested widely, including for floors.

3.2.3. Co-heating

Co-heating is a whole building heat loss measurement method, where a space or a building are kept at a constant internal temperature (usually for 1 to 3 weeks in winter) and the energy required to maintain this temperature is measured (Wingfield, 2010b). Co-heating gives a whole building Heat Loss Coefficient, which could be useful to identify relative changes between pre/post retrofit.
This method might be combined with simultaneous in-situ heat-flux measurements (Wingfield, 2010b). If in-situ floor heat-flux measurements are taken, they will contribute to a better understanding of the proportional and absolute floor heat-transfer as measured during the co-heating measurement conditions.

Given the extent of control required over the internal conditions to reach and be kept at steady-state, co-heating is usually undertaken in unoccupied houses, and actual occupancy patterns are not reflected in the co-heating outputs. Air-mixing fans are used to mechanically mix the air, affecting the rate of heat-flow through different mechanisms; this also does not reflect real occupancy patterns. Co-heating accuracy is strongly associated with external environmental conditions (Stamp, 2015).

3.2.4. Blower door tests

Air infiltration measurements by pressure testing can be used to understand the whole building air infiltration and ventilative heat loss through gaps and cracks. Air leakage can be quantified by the air-flow rate and is the leakage of air (m^3/hr) into and out of the building per metre square (m^2) of the building fabric at a 50Pa pressure difference between in-side and outside (ATTMA, 2010, CIBSE, 2015). This is undertaken with fan pressurisation – commonly known as 'blower door tests' (Sherman). Air leakage can also be defined by an air change rate: air changes per hour (ach^{-1}) express the air leakage by the volume of the space (CIBSE, 2015). As both are used in literature, for comparison purposes, both are referred to when communicating results in this thesis.

A blower door test result however cannot separate the ground floor's air leakage from the whole building leakage, unless the floor is separately pressurised. Some researchers have attempted to measure the air leakage of the floor void itself by placing the blower door fan in a large airbrick opening, e.g. DeWitt (1994). However, in the UK the airbricks are typically the size of one brick, i.e. 215 x 65mm, which is too small for the typical blower door fan used for air leakage tests.

This method also does not directly capture heat loss and the estimated air leakage rates are under test conditions, including taping up of ventilation openings and under (de)pressurisation situations and not actual building pressure differences. Furthermore external environmental conditions need to be sufficiently stable to undertake a blower door test (ATTMA, 2010, ISO, 2006), though blower door tests are not seasonally bound.

Nevertheless, blower door tests could give an estimate of the airtightness improvement of the floor pre/post intervention measures if no other interventions take place and if tests are undertaken in similar conditions pre/post intervention. This was done by Saint-Gobain (2014) in a lab to investigate the effect of interventions on building airtightness, including a floor intervention, and is further described in Section 6.5.1.

3.2.5. Tracer gas techniques

Suspended floor air leakage rates and paths can also be measured with tracer gas techniques as discussed in e.g. Hartless (1994), Edwards (1990), Basset (1988) and Williamson (2000). Typically, tracer gases are released and mixed in the floor void and their decay and release into the internal spaces above is measured over time. Tracer gases could be used to investigate the relative improvement in air-infiltration of the floor post-intervention. This technique also allows for the understanding of the flow of air between internal spaces (Riffat, 1988), and to understand the flow of air from void to other internal spaces under different environmental conditions.

However, this technique requires repeated testing to understand variability in different external conditions; it is expensive and tracer gases are difficult to mix in the generally tight in-situ sub-floor voids as noted by for example Edwards (1990) and Williamson (2000). While electrical fans in the airbricks can be used to mix the tracer gases in the void (Hartless, 1994) this changes the natural ventilation paths and hence changes exactly what is being measured. Given that fan-mixing is likely to affect in-situ U-value measurements, use of tracer gas techniques should be undertaken sequentially rather than simultaneously with in-situ heat-flux measurements.

3.2.6. Justification for selected research method

The research questions as set out in Chapter 2.9. focus this study on a single building element in in-situ conditions. The use of air-mixing fans in both co-heating tests and tracer-gas studies, preclude the study (or replication) of occupied dwelling conditions. Further, given the difficulty of isolating a single building element in most measuring methods, in-situ heat-flux measurements were considered to be the most suitable research method for the proposed research. Additional reasons in favour of in-situ U-value measurements are listed overleaf:

- In-situ heat-flux measurements have been used extensively for the investigation of the thermal performance of a variety of construction elements, including a limited number of suspended timber ground floors - see Chapter 2.4.2. In this thesis, in-situ heat -flux measurements of floors will add to the other in-situ results, investigate comparison with models and increase knowledge about the thermal performance of floors.
- In-situ heat-flux measurements have been used for some pre/post intervention studies, including for floors - e.g. Currie (2013) observed one point measurement on a floor pre/post insulation and Harris (1997) measured pre/post insulation floor performance in a test-cell - see Chapter 2.4.

Furthermore, a thermographic survey can support in-situ heat-flux measurement placement, while blower door tests will be used as a secondary research method where pre/post interventions take place to investigate the effect of the floor intervention on the overall dwelling's air leakage - see Chapter 6.5.1. Given the previously described limitations of pressurising the floor void itself as well as the difficulty of mixing tracer gases in confined floor void spaces, the investigation of sub-floor air change rates is considered beyond the scope of this research and is noted for future research purposes.

3.2.6.1. Overcoming limitations

There are however several limitations of in-situ heat-flux measurements in general and more specifically in relation to suspended timber ground floors, including issues raised previously in Section 3.2.1. and Chapter 2.4., such as practical aspects of measuring in occupied houses; limited floor measurements undertaken so far; measurement resolution issues and comparability to models and other sources. Other potential issues are resource limitations, inability to capture all heat loss mechanisms and confounding variables. However, with careful research design, the impact of these disadvantages might be minimised. A summary of the main limitations are listed below and overleaf, alongside how these limitations might be controlled for or minimised.

1. **Practical issues with measuring floors in occupied dwellings:** daily usage of floor surfaces limits where and how many sensors can be placed as well as the monitoring duration. This could be minimised by monitoring in an unoccupied dwelling, a thermal chamber or test-cell, however close replication of a typical floor construction, its junctions and a realistic approach to space-heating would be required to reflect typical construction and occupation - see Section 3.4 and research design in Chapters 4.3 and 5.2.
2. **Point measurements on a large surface area and difficulty to compare to models:** one point U-value is unlikely to be representative of the total element U-value (ASTM, 2007a) - see Section 3.3.2., Chapter 4.4.2.5, 4.4.3. and 5.3. for further discussion. Undertaking multi-point (i.e. high resolution) measurements will aid the understanding of the spread of floor heat-flow. Doing so will also support the understanding of the applicability of point measurements in pre/post comparisons, and support the testing of point U-value averaging techniques to obtain whole floor U-values to compare to models. Use of infrared thermography can help with sensor placement and with estimation of whole-floor U-values - see Chapter 4.4.2.
3. **Not all heat-loss may be captured**, such as the impact of air leakage of the floor on dwelling heat loss, which is also excluded in floor U-value models. For pre/post retrofit measures, blower door tests might give an indication of the floor's air leakage and any impacts arising from interventions. Monitoring heat loss with open and sealed airbricks might indicate the impact of floor void ventilation on observed heat-flow - see Chapters 4.4.4. and 5.3.7.
4. **Different measurement and analysis conventions and methods exist** which could affect U-value determination - this will be further investigated; full discussion in Section 3.3. and in Chapter 4.4.5 and 5.3.3.

5. **Time consuming to undertake and limited to the heating season:** field studies are limited to the winter heating season, limiting the number of studies that can be undertaken as well as limiting the time-scale of pre/post intervention monitoring - see Section 3.4. Access to an environmental chamber would disconnect measurements from the winter period, however this is subject to other limitations - see Chapter 4.3.
6. **Short-term and seasonally changing variables as confounders in pre/post intervention field studies:** changing external environmental conditions and seasonal changes of the ground will affect in-situ U-value estimates; there are potential confounding effects when undertaking pre/post intervention studies. This can be minimised by:
    - access to a thermal chamber with a replicated floor construction, such as the Salford Energy House; limitations of a thermal chamber are discussed in Section 3.4. and in Chapter 4.3.
    - analysing field data with dynamic methods instead of the more commonly used steady-state analysis techniques. Given that dynamic methods are not well characterised for suspended ground floors, steady state analysis was applied in this thesis.
    - measuring other external variables such as solar radiation, wind-speed as well as void airflow, and ground temperatures and heat-fluxes might give additional useful insights to support understanding of possible confounding variables; see Chapter 6.3.2.
    - Access to an unoccupied control house over the same period of the study might be useful; an occupied control house may introduce other variables such as occupant behaviour and different heating patterns, affecting the observed heat-flow - see Chapter 6.
    - monitoring heat-flow over a whole year or longer might provide a year-average U-value and other useful insights into the different mechanisms affecting heat transfer; this would also be aligned to current model assumptions. However in practice access to case-study dwellings is normally short-term, making long term longitudinal studies highly unlikely, especially if also monitored at high-resolution.

3.2.7. Other research methods used

The sampling of field studies and exploratory studies are described in Part 3 of this chapter (Section 3.4.) In addition to in-situ heat-flux monitoring, other in-situ studies were conducted: (a.) floor void conditions of a field study were monitored pre/post intervention over a short period only, as described in Chapter 5.2.3. and (b.) a brief thermal comfort study and the potential impact of air leakage on thermal comfort, as presented in Chapter 6.5. This study was also supported by visual observations and building surveying as described in the appropriate chapters. Additionally, literature reviews and software modelling tools were also used and are described in the following sections.

3.2.7.1. Literature review

This PhD thesis builds on existing research along seven key themes: (1.) Victorian dwellings and their construction (2.) physics of ground floor heat-transfer (3). in-situ heat-flux measurements and protocols (4.) floor void ventilation (5.) insulation of suspended timber ground floors (6.) mould growth and timber rot and (7.) thermal comfort. Other topics included statistical analysis techniques and experimental research design. Based on the literature review above and as set out in Chapter 2, it appears that only a limited amount of research is available specifically related to suspended ground floors and some of it spans different climates and construction methods and is often sparse on research and analysis methods used. Most literature was found via regular Web of Knowledge, library and Google Scholar searches as well as construction and industry databases. More detail of the key sources are listed in *Appendix 3.A*.

3.2.7.2. Modelling software

Floor U-value models as described in Chapter 2.3. were used to compare in-situ measured with modelled floor U-values. Separately, airtightness was investigated by estimating the impact of air leakage through floors on the whole dwelling with the Reduced Standard Assesment Procedure (RdSAP) - see Chapter 6.5.1. and below.

Floor U-value models are useful to give insights into estimated U-values of different floors modelled and to compare to in-situ measured U-values. As discussed in Chapter 2.3., it is unknown whether model simplifications and input assumptions have a significant effect on the accuracy of outputs and how this compares to in-situ measured floor U-values.

Certain interventions (airtightness measures) cannot be modelled with these U-value models, though this is also not taken into account when undertaking in-situ heat-flux measurements. An excel spread-sheet was set up to model the suspended ground floor U-value in accordance with RdSAP (BRE, 2011), CIBSE Guide A (CIBSE, 2015) and ISO-13370 (BSI, 2009) on which the former two models are based.

The superseded CIBSE-1986 model (CIBSE, 1986) was also included for comparison purposes. Default model input assumptions for material properties were used to model case-study floors, unless actual field data was available, for example from a building survey. Initial spreadsheet validation of the ISO-13370 model was achieved by comparing outputs with a commercially available floor U-value software calculator, BuildDesk U, which is based on ISO-13370 (BuildDesk, 2012). The CIBSE-1986 model was validated by use of a sample U-value floor calculation provided in CIBSE (1986). The use of the spreadsheet allowed the benefit of input and output transparency of the different variables, unlike commercial software. The same ISO-13370 and CIBSE-1986 equations were also scripted in R-software to undertake a brief sensitivity analysis of the different variables - see Section 4.4.3. As explained in Chapter 2.3 and as undertaken in this research, floor U-value models include adjustments for joist presence (after BSI 6946) unless stated otherwise but exclude linear thermal bridging; research of the latter has been noted for further research.

For whole dwelling **air leakage** (see Chapter 6.5.1.), measured results were also compared to models. BREVENT, a simplified model developed decades ago by the BRE to model building ventilation, was used to model stack-effect by e.g. Edwards (1990) but is no longer in use (Hartless, 2012). The software EnergyPlus was recently used by Gauthier (2014) to investigate the impact of ventilation through a suspended timber ground floor on thermal stratification. To do so, the entire building needs to be modelled in a complex dynamic model based on many input assumptions, e.g. assumed floor surface gaps and cracks, ground temperatures and airbrick openings and assumed void ventilation rate, often unknown and hence assumed inputs. Due to the assumed inputs and lack of validation of use of the model for this purpose, its accuracy is unknown and unverified. Finally, (Rd)SAP (also a whole building heat loss and airtightness model) also has a floor air leakage component - as discussed in Chapter 6.5.1. (Rd)SAP is a steady-state simplified model and the source of its floor air leakage assumptions are unknown. However, given that it is used for regulatory compliance in the UK (BRE, 2011), RdSAP was used in this research for brief comparison purposes.

3.3. Part 2: In-situ measurement methods

This section discusses in detail the main research method used in this PhD research, i.e. in-situ heat-flux measuring, and gives an overview of the main in-situ measuring standards followed by measurement uncertainty.

Overview of different standards

There are three main standards, all setting out in-situ heat-flux data collection, data and error analysis methods and standard presentation practices. These are listed below and summarised in *Appendix 3.C.*

1. ISO-9869 protocol (BSI, 2014) is the British accepted international standard and main point of reference for UK and European in-situ heat-flux standards;
2. Dutch draft CEN EN-12494 (CEN, 1996) similar to and based on the ISO-9869 (1994) standard;
3. the standard practice documents C-1046 (ASTM, 2013a) and C-1155 (ASTM, 2013b) from the American Society for Testing and Materials (ASTM).

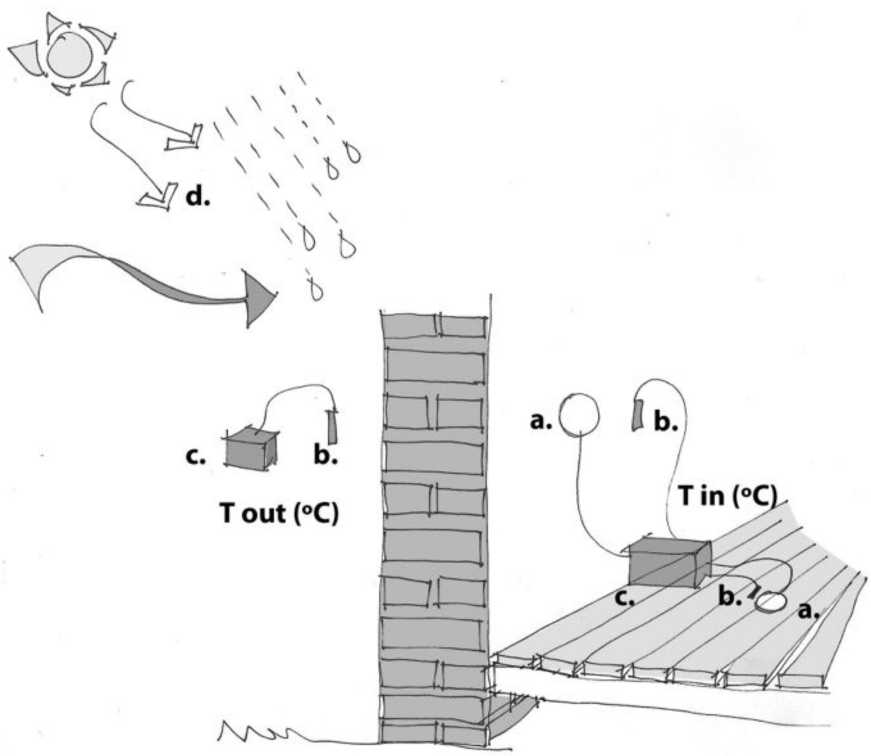

Figure 11. Schematic of typical in-situ U-value experimental set-up for walls and floors; a. heat-flux sensor; b. internal and external temperature sensors (surface or air temperatures, °C); c. datalogger; d. other variables such as solar radiation, wind and rain can also be measured to gain additional insights or for dynamic analysis (IEA, 2012).

In-situ heat-flux measurements are not direct measurements of thermal resistances or thermal transmittances but are undertaken by usually measuring heat-flux on one side and temperatures on both sides of a construction (T_i and T_e, °C)- as illustrated by *Figure 11.* The heat-flux sensor is usually temporarily fixed to the inside, warm face of the element, protected from heat-sources such as solar gain. Heat-flux sensors measure differential temperature across the heat-flux plate, generating a mV output (Q_{DL}), from which the conductive heat-flow rate (q, Wm^{-2}) is inferred using each sensor's unique sensitivity (or calibration factor, *ESen* in mVm^{2}W^{-1}, see *Equation 39.*). The internal and external temperatures (T_i and T_e, °C) and heat-flow rate (q, Wm^{-2}) are then combined in a measurement model to estimate the element's thermal resistance (R-value, *Equation 36.*) or the transmittance (U-value, *Equation 38.)*. The element under observation, and hence the heat-flux sensor, will be subject to convective and radiative influences in real monitoring campaigns, which in turn influence the measured rate of conductive heat-flow, but the different heat-flow influences cannot be isolated (D'Amelio, 2012a).

Equation 37. is referred to as the 'Average Method' in ISO-9869 (BSI, 2014) and CEN (1996) or 'Summation Technique' by ASTM (2007b). It is also referred to as "the ratio of means" in this thesis.

$R_T = R_{Se} + R_{Est} + R_{Si}$ - *Equation 36.*, where R_T is the total in-situ estimated construction element thermal resistance (m^{2}KW^{-1}); if surface temperatures are used to compute the in-situ estimated thermal resistance (*Equation 37.*), the assumed external and internal surface thermal resistances (R_{Se}, R_{Si} respectively) have to be added. Conversely, R_{Se} and R_{Si} are set to zero when utilising air temperatures (Baker, 2011b). R_{Se} and R_{Si} depend on the direction of heat-flow and can be obtained from BSI (2007).

$$R_{est} = \frac{\sum_{j=1}^{n}(T_{ij} - T_{ej})}{\sum_{j=1}^{n} q_j}$$

- *Equation 37.*, where R_{est} is the in-situ estimated R-value. T_{ij} is the internal temperature; T_{ej} is the external temperature and q is the heat-flux density (Wm^{-2}), derived from Equation 39. Index *j* identifies individual measurements and n is the number of measurements.

And $U = 1/R_T$ *Equation 38.*, where *U* is the final or total estimated in-situ U-value (Wm^{-2}K^{-1}) and is the reciprocal of the total thermal resistance R_T.

$q = Q_{DL}/E_{Sen} \quad [E_{Sen}\ in\ mVm^2W^{-1}]$ - *Equation 39.*, where E_{Sen} is each heat-flux sensor's unique sensitivity or calibration factor in mVm^{2}W^{-1} and Q_{DL} is the data logger acquisition component in mV, generated from the differential temperature across the heat-flux plate.

Equations 36. to 39. are a steady-state analysis of measurements usually undertaken in dynamic field conditions. When measuring in-situ heat-flow in buildings subject to environmental conditions, observed heat-flows fluctuate depending on dynamic effects such as heated/unheated periods, day/night and other environmental and seasonal fluctuations such as solar gain, wind, rain and thermal mass of the observed construction element.

In-situ U-values can be analysed taking into account dynamic effects by measuring different variables (e.g. wind-speed, solar radiation, thermal mass) as undertaken by IEA (2011-2015, 2012) and Gori (2014). A dynamic analysis method is also described in Annex B in ISO-9869 (2014). At present, steady-state analysis methods are more prevalent in industry and academia, hence this is also used for this PhD.

To minimise the impact of dynamic effects, all of the steady-state in-situ measurement analysis methods use a 'summation technique', whereby at every sampling time the thermal resistance is estimated by dividing the sum of the instantaneous temperature differences up to that time, by the sum of the density of heat-flow obtained up to that time[2] (*Equation 37.*). This procedure de-couples the temperature difference from the exact moment the heat-flux was measured as there will be a delay in heat-flux sensor response due to thermal mass (D'Amelio, 2012b). Through summation, the impact of dynamic effects and thermal mass time-lag on U-value results are minimised. For this reason, measurements need to be taken in 24-hour intervals, over a sufficiently long time period (with similar internal and external conditions) to ensure that the estimated U-value "*gives a good estimate of the steady state*" (BSI, 2014) and over time, the 'Average Method' considers dynamic effects to be negligible over the monitoring campaign - see also Section 3.3.1.

Despite this being referred to as the 'Average Method' (BSI, 2014, CEN, 1996) it is not the same as obtaining the average U-value as illustrated in *Figure 12.* and *Table 6.* As can be seen, the 'Average Method' (red line in *Figure 12.)* has a smoothing effect also expressed in smaller standard deviations (*sd*) for the smoothed data, compared to the instantaneous calculation of U-values (grey line) to obtain the mean U-value (or mean of ratios), with higher *sd*. Note that taking the *sd* of the 'Average Method' data is not suitable because the data come from a smoothing process instead of a natural sampling process and the data are not independent (see also Section 3.3.4.2.).

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[2] This is a ratio of sums, as per Equation 37., which mathematically corresponds to a ratio of means.

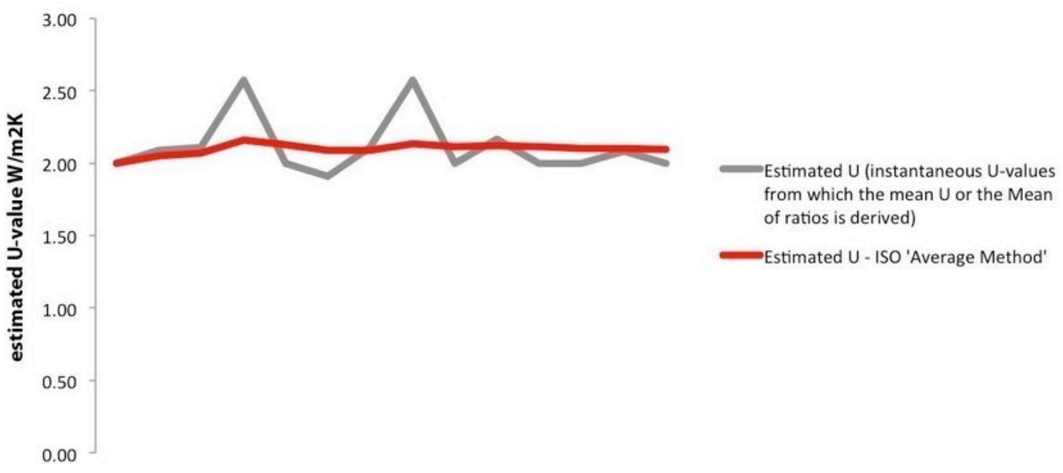


Figure 12. Compares fictive estimated U-values plotted according to the mean of ratios (in grey) and ratios of means (in red) to illustrate the difference in final estimated U-value.

Raw data			Ratio of Means or 'Average Method'				
ΔT	**q** (Wm^{-2})	**Estimated U from instantaneous raw data** ($Wm^{-2}K^{-1}$)	**ΔT**	**q** (Wm^{-2})	**ΣΔT**	**Σq**	**Estimated U - ISO average Method** ($Wm^{-2}K^{-1}$)
10	20	2.00	10	20	10.00	20.00	2.00
11	23	2.09	11	23	21.00	43.00	2.05
9	19	2.11	9	19	30.00	62.00	2.07
7	18	2.57	7	18	37.00	80.00	2.16
10	20	2.00	10	20	47.00	100.00	2.13
11	21	1.91	11	21	58.00	121.00	2.09
9	19	2.11	9	19	67.00	140.00	2.09
7	18	2.57	7	18	74.00	158.00	2.14
11	22	2.00	11	22	85.00	180.00	2.12
12	26	2.17	12	26	97.00	206.00	2.12
9	18	2.00	9	18	106.00	224.00	2.11
11	22	2.00	11	22	117.00	246.00	2.10
12	25	2.08	12	25	129.00	271.00	2.10
9	18	2.00	9	18	138.00	289.00	**2.09**
9.86 Mean ΔT	**20.64 Mean q**	**2.12 U MEAN (OR MEAN OF RATIOS)**	**9.86 Mean ΔT**	**20.64 Mean q**	**2.09 U RATIO OF MEANS (or Ratio of Sums)**		
0.20 sd of mean *(10% Proportion sd of U)*					***0.04 sd of mean*** *(2% Proportion sd of U)*		

Table 6. Fictive data used to plot Figure 12. and to illustrate the difference between the 'Average Method' or mean of ratios and the mean U-value (or ratio of means). The difference in standard deviation is particularly notable, with the mean U-value leading to a standard deviation of ±0.20 $Wm^{-2}K^{-1}$ versus the much smaller 'Average Method' standard deviation of 0.04 $Wm^{-2}K^{-1}$, illustrating the smoothing effect of the 'Average Method' on the data.

3.3.1. 'Valid' U-values

Equation 37. is applied at each measurement time; thus as more data is added, this 'summation technique' will converge to a steady U or R-value, the value of which is considered to be the best estimate of the thermal transmittance or resistance, as long as the sensor was not subject to direct solar gain and the element's thermal properties remained the same throughout the measurement (or the change of heat stored in the element is a small proportion of total heat flow) (BSI, 2014). This convergency to a final U-value can be seen by the red line in *Figure 12.* in Section 3.3., which also highlights the smoothing impact of this technique on the data; implications for this are also discussed in Section 3.3.4.2.

Different convergence criteria are set in the different standards to define the 'valid' U-(or R)-value. In ISO 9869 (BSI, 2014) and CEN (1996) there are 3 test criteria:

(1.) the monitoring period must be minimum 72 hrs long and always taken over a full 24 hour period;

(2.) the final U-value must be within ±5% (ISO 9869) or ±2% (CEN, 1996) of the value obtained a complete 24hrs prior and,

(3.) the final U-value obtained in the first 2/3rds of the data (based on full 24-hour periods only) should be within ±5% (ISO 9869) or ±2% (CEN, 1996) of the U-value obtained after analysing the last 2/3rds of the data, again based on complete days.

It is considered that the element's thermal mass is accounted for by measuring over a long enough period, depending on measuring conditions and the observed construction element. For solid brick walls, monitoring campaigns can be as long as 14 days (Gori, 2014) especially in occupied houses (BRE, 2014b) and sometimes longer (Baker, 2011b) to meet criteria (2.) described above. It is unclear what the measuring time frame of suspended timber ground floor structures might be; Isaacs (1985b) suggested a 24 hr periodic day/night cycle and a three to four day measuring period (though a longer term seasonal cycle would also exist).

While longer measuring campaigns with summation technique analysis increase the likelihood of meeting criteria (2.), it might decrease the likelihood of meeting criteria (3.). This is because, in general, the longer the measuring period, the more likely that the environmental conditions, such as solar gain and wind-speed, are dissimilar between the start (the first 2/3rds of data) and the end of the monitoring period (i.e. the last 2/3rds) and the more likely that seasonal effects, including seasonal thermal mass effects, influence the observed heat-flow. In practice, the above criteria might not be used; particularly criteria (3.) is often not reported, and instead valid U (or R)-values are inferred by visually assessing if the value converges to a constant value, e.g. Cox-Smith (2008).

3.3.2. Heat-flux sensor placement, whole element U-values and model comparisons

In-situ measuring campaigns are often limited by access to equipment and the available measurement locations in occupied dwellings, due to placement of furniture and occupant activities. Resource costs and such practical issues might be the reasons why generally just one or a few heat-flux sensors are mounted on a construction element, as illustrated by low-resolution floor monitoring studies in Chapter 2.4. However, in-situ measured U-values are point-measurements on a construction element, which measure the heat-flow through a sensor area of about 30mm diameter within an 80mm diameter heat-flux plate (and surface temperature sensors typically have a smaller sensor area). Clearly, estimating heat-flow of an entire element based on a single or a few point-measurements is unlikely to be representative of the whole construction element (ASTM, 2007a), though this is likely to depend on the construction element and might make comparison with modelled U-values difficult. Hence, depending where sensors are placed, whole element U-values can be over- or under-estimated when based on single or few point-measurements.

It is therefore important that sensors are placed to either be representative of the observed construction surface and to avoid (or purposively investigate) specific unrepresentative areas, such as local inhomogeneities or thermal bridging (BSI, 2014) - depending on the monitoring purpose. For example heat-flow is likely to be influenced by thermal bridging when measuring heat-flow within 200-400mm of window/door openings and floor/wall and wall/wall junctions (Doran, 2008), hence these areas are unlikely to be representative of the whole fabric element but could still be of interest to investigate or characterise.

Combining point U-values into a 'whole element U-value' is hence useful to understand total estimated thermal transmittance and to compare with models; the latter usually predict average U-values of whole fabric elements in steady state conditions - see Chapter 2.3. A whole element in-situ U-value may be estimated by "*averaging the results of several heat-flow meter measurements*" (BSI, 2014) or from area-weighted averages "*using appropriate groupings of sensors in representative subsections*" (ASTM, 2007b) - different techniques are explored, tested and refined in Chapter 4.4.2.

Models will however "*not always agree exactly with measured U-values measured on site*" (McMullan, 2002); ISO-9869 (BSI, 2014) and CEN (1996) state that differences between measured and modelled U-value estimates are significant [only] if >20% and this is due to a number of reasons which should be taken into account in such comparisons. Divergence from predictive models might in some cases be explained by model input assumptions that do not reflect actual variables due to difficulty in determining existing fabric characteristics (e.g. material conductivities, thickness, assumed surface resistances, see e.g. May (2012) and Gentry (2010)); but might also be explained by in-situ measurement issues such as lack of representative surface under investigation and measurement issues such as determination of representative environmental temperatures (BSI, 2014) - as discussed in Section 3.3.3. Sensor placement on seemingly homogenous construction elements (such as mortar joints, air-gaps and hidden services) may not be homogenous and contribute to different heat-flow patterns than modelled (Byrne et al., 2013, Siviour, 1994, Cesaratto et al., 2011, Cesaratto and De Carli, 2012).

The use of infrared thermography can be useful to identify such (un)representative areas to investigate for in-situ monitoring (ASTM, 2007a, BSI, 2014). If a large spread of temperatures is observed from infrared images, strategic placement of several sensors will be necessary to understand the entire element's in-situ heat-flow (ASTM, 2007a) and to be representative of the heat-flow of the entire element - this approach was used throughout this thesis. Infrared thermography can also be useful to check if the greater region surrounding the sensor site is similar to interpolate to a larger area (ASTM, 2007a) and to estimate whole element U-values - see Section 4.4.2. However interpolated values will be less accurate than the observed values (ASTM, 2007a). Evidently, the larger the purposeful coverage of heat-flux sensors on the surface, the greater the certainty of the whole surface thermal transmittance under those measuring conditions - see Section 3.3.4., Chapter 4.4.2 and 5.3.

3.3.3. Temperature measurements

The standards do not stipulate minimum temperature differences (ΔT) between both sides of the observed construction element, although ideally in-situ measurements are undertaken when there is a sufficient ΔT in order to observe a sufficiently large heat-flux outside the instrument accuracies. Optimal ΔT are depending on sources: >4ºC and ideally >10ºC (Cox-Smith, 2008) or between ≥7ºC and ≥10ºC (IEA, 2011-2015, Siviour, 1982, Doran, 2008, Baker, 2011b, McIntyre, 1985, Desogus et al., 2011). However lower temperature differences can still give valid, albeit less accurate in-situ results (Desogus et al., 2011, Byrne et al., 2013, CEN, 1996, Trethowen, 1986) because, proportionally, the instrument error increases with smaller ΔT. Hence the increased importance of both temperature sensor accuracy and precision with a small ΔT to avoid large proportional measurement errors.

Another issue to take into account is where these temperatures are actually measured, as discussed in the following sections.

3.3.3.1. Air temperatures as a proxy for ambient temperatures

Environmental (ambient) temperatures are required for U-value determination, however air temperatures are often used to substitute ambient temperatures (BSI, 2014, IEA, 2012) as ambient temperatures cannot be directly measured and are not constant in a room (BSI, 2014). Ambient temperatures are a combination of radiation and convection transfer coefficients, space emittance (which includes the emissivity and view factor of all the surrounding surfaces), air temperature and the radiant temperature 'seen' by the observed surface.

Only air temperature and radiation transfer coefficients can be more easily determined (BSI, 2014). However due to the inhomogeneity of air temperatures in rooms caused by a complex interplay of convective currents in the room from heating elements and from ventilation (and surfaces at different temperatures that create these currents), vertical (and horizontal) temperature gradients exist (BSI, 2014, Gauthier, 2014, MING XU, 2001). As such, it is unclear where to measure air temperatures in the room for U-value determination - this is explored in Chapter 4.4.5. Given the above, depending on the location and condition of measurement, a U-value estimated from air temperatures will vary across the fabric element, even if the thermal resistance (R-value) of the element is homogenous (BSI, 2014).

As such, significant disparities might arise between modelled values and measured U-values depending on the reference temperatures used and "*a U-value measured in situ may not be the appropriate U-value for use in heat loss calculations if different temperatures are involved in the two cases"* (BSI, 2014). ISO-9869 assumes a ±5% random error associated with U-value "*temperature variations within the space and differences between air and radiant temperatures*" (BSI, 2014) - as discussed in Section 3.3.4.

The question where to measure the air temperature is further complicated by the practicalities of placing sensors, especially in occupied houses. Siviour (1982) suggests internal air temperatures to be measured within 500mm from the heat-flux sensor for in-situ wall measurements while Doran (2001) placed air temperature sensors 10mm away from the heat-flux sensor on the wall (as also suggested by EST (2006)) and *"a few centimetres from the centre of the heat flux plate"* by BRE (2014a); though it is unclear how such sensor locations were determined while their applicability for floors is unknown. For solid ground floors, Trethowen (n.d.) observed internal room temperatures at the floor surface and at 300mm and 2000mm high. However no standard heights and locations are used (if specified), making comparisons between studies problematic.

While a U-value is typically estimated from 'air to air' environments (BSI, 2014) (which is usually also the model assumption (IEA, 2012)), surface to air temperatures are often used instead as this can be more practical to determine - as discussed in the following Section 3.3.3.2.

3.3.3.2. Use of surface temperatures in U-value estimation

Typically, surface temperatures are used for R-value estimates of a building element; the addition of assumed surface thermal resistances is required for the determination of a U-value or the total thermal resistance (R_T) of the element when surface temperatures are used (CEN, 1996, Baker, 2011b). Where internal surface temperatures and external air temperatures are used for the estimation of U-values, as done here in this study, the addition of an internal surface thermal resistance as per - *Equation 40.* is required - see e.g. Baker (2011a), Rye (2011), Rhee-Duverne (2013), Currie (2013).

$$U_{est} = 1/\left(\frac{\sum_{j=1}^{n}(T_{Sij} - T_{Sej})}{\sum_{j=1}^{n} q_j} + R_{Si} + R_{Se}\right)$$

- *Equation 40.*, where T_{Si} is the surface temperature of the floor in the room and R_{Si} is the internal surface thermal resistance, taken to be 0.17 m^2KW^{-1} in accordance with BSI (2007) while R_{Se} is set to zero if external air temperatures (T_{ae}) are used instead of external surface temperatures (T_{Se}).

Surface temperature sensors are to be placed under or near the heat-flux sensor, and both should be of the same colour and emissivity as the observed surface as recommended by ASTM (2007a) and ISO-9869 (BSI, 2014); some studies place surface temperature sensors on the heat flux sensor - see e.g. Rye (2010) and Baker (2011b).

When using surface temperatures instead of air temperatures, the addition of constant surface thermal resistances may not be suitable in all situations (BSI, 2007, Mirsadeghi et al., 2013). Surface resistances are influenced by the radiative and convective transfer coefficients ($Wm^{-2}K^{-1}$) and surface emissivity (BSI, 2007, BSI, 2014), which are unlikely to be constant over an entire element's surface area or a range of conditions (BSI, 2014) or as assumed by standards. For instance, external surface resistances vary in accordance with external environmental conditions and are inversely proportional to wind-speeds; for example a wall's external surface resistance R_{Se} decreases from 0.08 m^2KW^{-1} to 0.02 m^2KW^{-1} when wind-speeds increased from 1m/s to 10m/s respectively (BSI, 2007) - see *Table 7*. Convective airflows are likely altered by furniture placement, air infiltration and heating sources so the assumption that an element's surface is subject to constant wind-speed, airflow and constant radiative heat-flow throughout an enclosure is unlikely to be the case as observed by Emery (2007).

Heat-flow direction	**Horizontal (e.g. wall)** (m^2KW^{-1})	**Upward (e.g. ceiling)** (m^2KW^{-1})	**Downwards (e.g. floor)** (m^2KW^{-1})
Internal surface resistance, R_{Si}	0.13	0.10	0.17
External surface resistance, R_{Se} 4 m/s windspeed - typical assumed	0.04	0.04	0.04
External surface resistance, R_{Se} 1 m/s windspeed	0.08	-	-
External surface resistance, R_{Se} 10 m/s windspeed	0.02	-	-

Table 7. Typical assumed surface resistances for surfaces in contact with air - adapted from BSI (2007); downward heat-flow experiences the greatest internal surface resistance and upward heat-flow the lowest resistance.

Determining the actual surface resistance in the field is difficult (Isaacs, 1985b) and the use of constant surface resistances may not reflect the actual, variable in-situ conditions at the time of measurement (Isaacs, 1985b), affecting U-value estimates. This might lead to disparities with modelled U-value results and was also noted by BRE (2014a) for in-situ heat-flux wall measurements. However, the addition of assumed surface resistances to well-insulated elements is unlikely to have a significant effect on the final estimated value (Isaacs, 1985b). Counter to this, adding a surface thermal resistance to uninsulated elements with a small thermal resistance has a greater proportional impact and such addition is likely to be of greater influence on the final estimated U-values - see Chapter 6.4.2. The addition of R_{Si} could be a systematic error for all sensors, or a systematic error for some sensors; for example near sources of turbulent airflow over the floor surface, the R_{Si} might be overestimated compared to other locations without such turbulent airflow influences, however this is uncharacterised at present for floors. The impact of the addition of surface thermal resistances on in-situ U-value estimations is at present poorly characterised and beyond the scope of this research for detailed analysis.

3.3.3.3. Use of external air temperatures or void air temperatures for estimation of floor U-values?

As discussed in Chapter 2.4.2, different in-situ floor heat-flux data collection techniques are used, including measurements from the internal environment (surface or air) to the void or to the external environment. For example, Miles-Shenton (2011) uses internal air to external air for estimation of floor U-values, while Isaacs (1985b) uses internal surface to void air temperatures to estimate R-values (though this includes floors with open foundation walls exposed to the external environment) and Currie (2013) uses the same to estimate a U-value; though the authors also estimate U-values from skirting air temperature to external air temperature (Stinson, 2012). Harris (1997) estimates thermal resistances and U-values from internal air to void air temperatures, specifically to investigate heat-flow reduction to the floor void after insulation interventions (Harris, 2013), while no detail is provided by Baker (2011a).

As U-values are calculated or modelled from the internal to the external environment ((Szokolay, 2008) and given that the floor U-value model ISO-13370 uses the external environment (BSI, 2009), the external environment will be used in this study to enable comparison of in-situ estimated U-values with models and to understand the actual thermal performance of the floor system. Thus, throughout the research hereby presented, all U-values are calculated using external temperatures, rather than floor void temperatures.

3.3.4. Uncertainty and error estimation

This section gives an overview of measurement uncertainty and errors and critically reviews different existing in-situ measurement error propagation techniques, prior to presenting the error propagation method developed and proposed for this thesis.

3.3.4.1. Sources of error and uncertainty

Uncertainty in in-situ heat-flux measurements can be associated with measurement techniques used (for example, where air temperatures are measured), as well as the addition of constant surface thermal resistances where surface temperatures are used - see Section 3.3.3. In addition, uncertainty in obtaining a whole element U-value is associated with the number of point-values used to estimate this whole element U-value and how representative the observed point-values are of the entire fabric element (Section 3.3.2). Uncertainty with in-situ field measurements is also associated with seasonal influences and the natural variability of heat-flow through a construction element (and is affected by timing of the monitoring campaign) - this is further discussed below.

Moreover, like all field measurements using instruments, in-situ heat-flux measurements are affected by the conditions of measurement and instruments used, which have errors associated with them. It is for these reasons that, even when measuring over sufficiently long periods, the in-situ method in non-steady state conditions is not a high precision method (BSI, 2014). The act of measuring affects what is being measured: for instance, placing a heat-flux sensor on a surface inherently affects the characteristics of what is being attempted to be measured (Childs, 1999), leading, for example, to random or systematic deflection and reflection errors. This means that measurement results can only ever be an estimate of the true value rather than the actual true value. It is therefore important that these errors are as best as possible accounted for as this affects the measurement results, confidence in findings and comparability between different sources, published literature, specifications, standards, models (JCGM, 2008, Czichos, 2011) and comparison of the heat-flow reduction potential of intervention measures. For example, it is generally accepted that the difference between measurements (and hence also the efficacy of interventions) is only 'demonstrated' if measurement uncertainties do not overlap (Taylor, 1997).

However, the exact number of errors and of possible confounders, and the magnitude of their effect is not known, despite influencing the estimated result. These errors can be systematic or random. **Systematic errors** usually relate to accuracy and spread the readings around some displaced, but not true value (Squires, 2001) and cannot be controlled for by repeated measurements (Taylor, 1997). Systematic errors include instrument accuracy (how close it is certified to a known value), instrument erroneous calibration, research practice and design (e.g. differences in sensor fixings), and their exact influence is usually unknown but should instead be minimised for by careful research design and practice. Though small, the systematic additional influence of the thermal resistance of the heat-flux sensor itself of 6.25×10^{-3} m^2K/W (Hukseflux, 2012) can be accounted for by adjusting for (i.e. deducting this factor) in R- and U-value estimations, as has been done in this research. Systematic errors could be only present (or absent) in certain conditions and could be systematic for each sensor but random between sensors or for a collection of sensors, making error estimation difficult. **Random errors,** usually associated with the precision (or repeatability) of measurements, are equally likely to be positive or negative and are always present in an experiment and causes "*successive readings to spread about the true value of the quantity*" (Squires, 2001). Random errors can be reduced by repeated measurements and might be revealed statistically from the spread/variation of repeated measurements (Taylor, 1997). Random error sources include equipment set-up and researcher and occupant influence, though these might also be systematic errors or have systematic components. Usually results are accurate if they are "*relatively free from systematic errors, and precise if the random error is small*" (Squires, 2001) - clearly both are important.

Slightly different errors are estimated in different standards and are summarised in *Appendix 3.D.,* adapted from Pelsmakers (2012). Given that ISO-9869 (BSI, 2014) is the UK and EU accepted protocol, its identified errors are summarised below, and was used in this thesis as a basis for uncertainty estimation.

As described in Section 3.3.3. there is difficulty to measure accurate temperatures which reflect the heat-flow path and this will create uncertainty, estimated at ±5% by ISO-9869 for "*temperature variations within the space and differences between air and radiant temperatures*"(BSI, 2014). In addition, there will be instrument errors (±5%, (BSI, 2014)) and contact errors (±5%, (BSI, 2014)) could arise if leaving a small gap between the sensor and the surface and (or) changing the airspeed around the sensor; contact error was found to be ≤2% with airspeeds up to 1m/s (Bales, 1985). It should also be noted that airflow through the floor board gaps could create turbulence around the sensors and also affect any airflow between the sensors and the surface, though the airspeed around the sensors is unknown and this uncertainty is uncharacterised.

The mounting of the sensor on the surface changes the heat-flow that goes through the undisturbed surface, which can lead to operational deflection errors (Cesaratto et al., 2011, Childs, 1999, Trethowen, 1986); it is estimated by ISO-9869 (BSI, 2014) at ±2 to ±3% error though a slightly larger deflection error of ±4% is suggested by Doran (2008). Furthermore, masking tape smoothed over the sensor's edges can minimise "*the differences in turbulent flow over the sensor compared to the adjacent wall.*" (Bales, 1985). Similar fixing strategies are likely to be relevant for floor sensor fixings. Additionally, ISO-9869 (BSI, 2014) estimates a ±10% error for "*errors caused by the variations over time of the temperatures and heat-flow*", i.e. natural variability.

However, the natural variability of a U-value is not a measurement error but a real characteristic of an element's actual thermal transmittance in dynamic situations; i.e. U-values are not constant but change when subject to e.g. changes in radiation and airflow over time. To discuss this conceptual difference, it can be helpful to think of the identified errors as 'intrinsic' and 'extrinsic errors' (Bales, 1985) and separate these from the natural variability of U-values - as categorised in *Table 8*. Intrinsic errors are those related to instrument accuracy, while extrinsic properties are associated and contingent on the measurement application and technique used (Bales, 1985), i.e. related to measuring conditions. For example extrinsic errors come from how ambient temperatures are determined and from sensor fixing methods such as deflection and contact errors.

Instrument error (Intrinsic)	Measuring condition/equipment set-up errors (Extrinsic)	Inherent property (not a measurement error)
± 5% Accuracy heat-flux and temperature sensors[3]	±3% Operational/deflection error	±10% Natural variability U
	±5% Contact error	
	±5% Temperature sensor location measurement error; only for U-values[4] when air temperatures used.	
Total ISO-9869 error	$\geq \sqrt{5^2 + 3^2 + 5^2 + 5^2 + 10^2} = \pm 14\%$ - *Equation 41.* - see also Section 3.3.4.2.	

Table 8. Summary of ISO-9869 estimated measurement uncertainties; categorisation by author.

As surface temperatures are used for estimation of R-values (BSI, 2014), the latter ±5% error 'temperature location measurement error' is considered applicable only to U-value estimates (D'Amelio, 2012a) where air temperatures are generally used - this is further discussed in Section 3.3.4.3.

3.3.4.2. Different error propagation methods

Following on from the previous overview of ISO-9869 estimated errors, an overview is provided here of the ISO-9869 error propagation method as well as Baker's (2011) error propagation technique as this is used by several other researchers in the UK, followed by any other techniques.

[3] Often 'accuracy' issues tend to be systematic errors; instrument documentation tends to state instrument calibration accuracy as a ± value; the ± value suggests random error, which it is for a range of sensors, but systematic (but unknown in which direction) per sensor. Given that this systematic error is known, and its direction could be either way, it might be offset by other random errors, hence combination in the quadratic sum with other (random) errors is appropriate. Taylor (1997, p106-107) argues that systematic errors combined with random errors in quadrature could be combined to give a *"reasonable estimate of our total uncertainty, given that our apparatus has systematic uncertainties we could not eliminate"*. Other systematic calibration errors can however occur in determining the accuracy of instruments, which could lead to an offset in the instrument accuracy, which is often only revealed when measuring the same quantity with different sensors side-by-side or upon re-calibration.

[4] The ±5% error is not directly stated in ISO-9869 but interpreted from the addition of another ±5% error in the quadratic sum and arithmetic sum not accounted for above - as also interpreted by D'Amelio (2012a).

A. ISO-9869 error propagation

For in-situ heat-flux measurement errors, it is usually assumed that errors are independent and that data is normally distributed[5]. As errors are likely to be independent (D'Amelio, 2012a), the most appropriate final uncertainty estimate is around ±14% for U-values and ±13% for R-values, obtained from the quadratic sum of individual errors (see *Table 8.)* and as per *Equation 41.* If errors are not independent, the most appropriate final uncertainty is ≤±28% for U-values and ≤ ±23% for R-values, as derived from the sum of the individual errors (*Equation 42.*); though usually independency of errors is assumed (D'Amelio, 2012a) and hence use of *Equation 41.* is usually applied.

$\geq \sqrt{5^2 + 3^2 + 5^2 + 5^2 + 10^2} = \pm 14\%$ - *Equation 41.* (Quadratic sum of the individual errors for U-values)

and $\leq 5 + 3 + 5 + 5 = 10 = \pm 28\%$ - *Equation 42.* (Sum of the individual errors, if errors are not random or are dependent, for U-values)

It should be noted however that the treatment of the ±10% natural variability of U as a source of error is not ideal and this is further discussed in Section 3.3.4.3.

While ISO-9869 is the main accepted protocol in Europe and the UK, the above error propagation technique is not generally used in the UK for determination of measurement uncertainty; see e.g. Baker (2011b), Rye (2013), Currie (2013) and Rhee-Duverne (2013). It is unclear why this is the case. Furthermore, many other sources appear to use lower uncertainty methods than the ±13% to ±14% ISO-9869 estimated error stated above. While Bales (1985) estimates that a total error of ±5% is attainable for heat-flux measurements in laboratory conditions, they are more likely between ±5 to ±20% for in-situ field measurements and can even be up to 100% if no care is taken (though it does not mention how to prevent such large errors). Modera et al in Bales (1985) discusses how control of the internal environment can reduce U-value error estimates; however this is difficult to achieve in occupied houses but could be achieved in unoccupied houses and in environmental chambers. Typically, industry papers assume or derive final in-situ estimated field errors in the region of ±10%, see e.g. Cox-Smith (2008), Isaacs (1985b), Siviour (1982), Flanders in Bales (1985) and Rye (2012). Though Birchall (2011) estimated in-situ uncertainty as high as ±15%.

[5] This is nowhere explicitly stated, however is implied by sources when they (a.) combine errors in the quadratic sum, which is a statistical treatment for independent errors and (b.) when standard deviations are used, which is a statistical descriptor of normally distributed data - see Taylor (1997).

It is however not always clear how these figures were derived nor whether they are representative of typical in-situ measurements. Doran (2008) uses another error propagation method, while e.g. Rhee-Duverne (2013), Currie (2013) and Rye (2012) use Baker's (2011b) error propagation technique, which generally leads to slightly lower uncertainty estimates compared to ISO-9869 - as further discussed in following section B below.

The implication of using the ISO-9869 error estimate means that there needs to be a difference of about 28%[6] between pre/post intervention U-values, in order to have non-overlapping error estimates and demonstrate some efficacy of the intervention.

B. Baker's error propagation

As mentioned above in section A., several sources use the error propagation method reported by Baker (2011b), which combines the standard deviations of moving average U-values with specific individual instrument precisions (U_{err_q}; U_{err_Ti} *and* U_{err_Te}), as stated by the instrument specifications, in the quadrature sum (see Equations 43. and 44., after Baker). Baker (2011b) applies this to 14 days of data, split in seven days, using a 24 hour sliding window; see *Figure 13.* for illustration of the sliding window. This procedure gives eight U-values for a 14 day measuring period; *sd* in *Equation 43.* is the standard deviation of these eight obtained U-values. The use of the standard deviation *sd* in *Equation 43.* is a method to determine the uncertainty arising from the environmental changes in the external environment which impact on the final estimated U-value, as also defined by ISO-9869 as 'natural variability in U'.

$$dU = \sqrt{(U - Uerr\_q)^2 + (U - Uerr\_T_i)^2 + (U - Uerr\_T_e)^2 + sd^2}$$

- Equation 43., where *dU* is the overall uncertainty and U estimated in accordance with *Equation 40.*; *Uerr_q* is the U-value obtained after adding the heat-flux sensor precision error, *err_q*, to each measurement as *Equation 44.* below and after Baker (2011b).

$$Uerr\_q = 1/\left(\frac{\sum_{j=1}^{n}(T_{ij} - T_{ej})}{\sum_{j=1}^{n}(q_j + err\_q)} + R_{Si} + R_{Se}\right)$$

- Equation 44.

Note that the internal temperature sensor error (*Uerr_*T_i) and external temperature sensor error (*Uerr_*T_e) were similarly calculated as per *Equation 43.*

[6] I.e. based on the quadratic sum and assuming independent errors; an error estimate of ±14% applies to each point U-value, hence a ±28% difference leads to no overlapping error margins.

As Baker (2011b) explains: "*In order to determine the error each measurement will have on the U-value estimate, the U-value calculation is repeated with each measured parameter perturbed by its error in turn.*" And with regards to the moving average U-values: "*i.e. the first period is the average U over day 1 to day 7; the second period day 2 to day 8; etc. The standard deviation (s.d.) of these N averages of U can then be calculated, which will give some indication of the uncertainty of the estimated U-value.*" (Baker, 2011b). However, some issues might arise with this method:

- Using a sliding window to calculate successive U-values leads to a low standard deviation (*sd)*: each sliding window has ~85% data in common with the previously obtained U-value; only the final U-value and first U-value obtained this way have no data in common, as illustrated by *Figure 13.a.* The sliding window violates the assumption of independence of the other 'sliding' errors when applied in the quadrature sum[7].
- The standard deviation *sd* is applied to U-values which were obtained from the ratio of means or 'Average Method' (see *Equation 45.*). As illustrated by *Figure 12.* in Section 3.3., this is itself a method which 'smoothes out' deviations, so is biased towards a lower *sd* - as illustrated in *Table 6.,* Section 3.3. Statistically, the use of *sd* should only be applied to the mean (of normally distributed data) (Taylor, 1997, Squires, 2001) as per *Equation 46.*, and not to smoothed 'Average Method' data.

$$U_{est} = 1/\left(\frac{\sum_{j=1}^{n}(T_{Sij} - T_{eaj})}{\sum_{j=1}^{n} q_j} + R_{Si}\right)$$

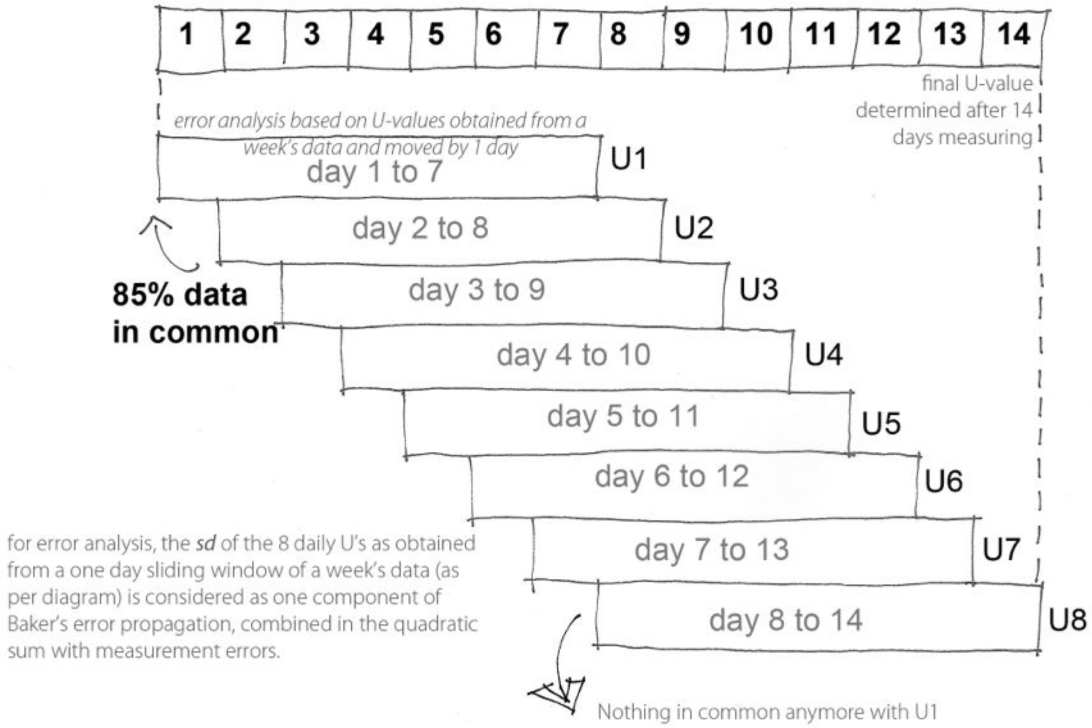
- *Equation 45.*, ratio of means (ISO-9869)

$$U_{mean} = \frac{1}{n}\sum_{j=1}^{n} 1/\left(\frac{(T_{Sij} - T_{eaj})}{q_j} + R_{Si}\right)$$

- *Equation 46.*, mean of ratios

- Baker's error propagation was developed for a 14 day monitoring period (see *Figure 13.a.)*; if less data is available, the data will need to be split in for example smaller windows with a shorter sliding window, though it is unclear whether thermal mass effects will stabilise in this shorter time-frame. To illustrate this see *Figure 13.b.* which uses a shorter 2 day period and 1 day sliding window if - for instance - only 8 days of data are available.
- Baker's method only includes instrument precision error and the *sd* from smoothed data, and excludes other likely errors identified in Section 3.3.4.1. (e.g. contact error, edge effect errors, errors arising from temperature sensor locations), hence biasing the error estimate low.

[7] Combining errors in the quadrature sum is usually only valid if the errors are independent see Taylor (1997, p 60-61).



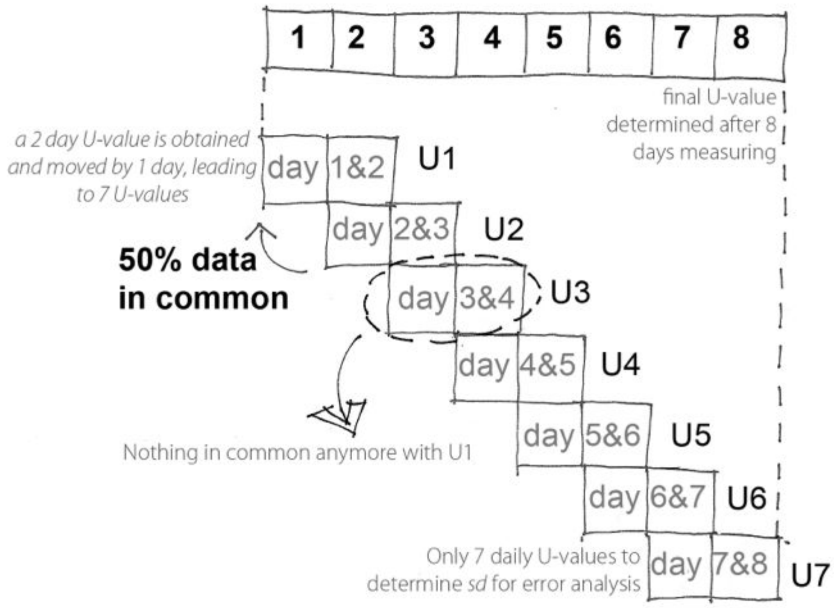


Figure 13.a. and b. are diagrammatic representations of Baker's (2011) moving average U-values to calculate the standard deviation. Figure a. (top) is obtained from 14 days of data with error analysis based on U-values obtained from weekly (7 day) data and moved by 1 day. For illustrative purposes, figure b.(bottom) is applied to just 8 days data: a 2 day U-value is obtained and moved by 1 day, leading to 7 U-values; this is likely to give higher sd compared to figure a., as less data in common (50%).

C. Other techniques

Some research, e.g. Byrne (2013) reports small total error estimates and mentions the use of 'standard deviations' with no further detail whether this is the standard deviation or the standard deviation of the mean (SDOM, also standard error) nor whether this is applied to the 'Average Method' or to the mean U-values. Following on from previous discussion, statistical techniques such as *sd* and SDOM should only be applied to mean values (and where normally distributed).

In the field, *sd* of the mean is expected to be large if taken on instantaneous measured values at short intervals, as there will be large deviations between day/night; heated/unheated patterns and other changing external conditions - these are not errors however but expected variations in differently measured U-values as discussed further below in Section 3.3.4.3. Conversely, in an environmental chamber, *sd* is expected to be significantly smaller as the environmental conditions are kept at (near) steady-state.

Even if appropriately applied to the mean U-value distribution, use of *sd* and SDOM on its own might not be suitable as an expression of final uncertainty: *sd* (and SDOM) include the initial settling time and environmental conditions and (random) researcher error which affected that sensor, but excludes uncertainties associated with fixing methods (contact/defection) and the uncertainty associated with ambient temperature determination.[8] In addition, use of SDOM, which takes into account both the spread of the data (the *sd*) and the sample size, is unlikely to be suitable as it is based on the assumption that the measurements are independent repeated measurements. For each point U-value, heat-flow is being measured in the same location over time at certain intervals for a specific duration, but in-situ measurements in the field are subject to changing environmental conditions so measurements are never repeated under the same conditions.[9] Moreover, field data is sampled in given measurement intervals, which exacerbates the autocorrelation effects associated with the fact that environmental conditions do not vary at random but in a gradual and correlated way through time. Even in an environmental chamber there are small differences in the steady-state conditions (so no repeated measurements). Given that (as per above discussion), other errors are also excluded, SDOM is hence also unlikely to be a representative error estimate of lab U-value estimates.

[8] Such errors are important to include, especially also where comparing between sensors as each sensor will have been subject to different environmental conditions compared to another.

[9] E.g. different temperatures during day/night and heated/unheated periods.

3.3.4.3. Applied error estimation and propagation method

The error propagation method proposed for in-situ U-value measurements in this thesis research builds on the ISO-9869 standard and Baker's error propagation method as discussed in the previous Section 3.3.4.2. The same ISO-9869 estimated intrinsic and extrinsic errors were accepted for this thesis research - see *Table 8*. As previously discussed, the natural variability of in-situ heat flux measurements under changing, dynamic environmental conditions are listed in ISO-9869 as a ±10% uncertainty, while Baker (2011b) uses the *sd* of *moving average U-values* obtained from the ratio of means, as an attempt to capture this natural variability 'swing' (Section 3.3.4.2.).

Instead of either of these methods, the natural variability during the monitoring period could be estimated by using a statistical approach of one of the properties of the data distribution, such as the *sd* around the mean, obtained from the mean of ratios. As per - *Equation 47. or Equation 48.,* depending on use of internal surface or air temperatures respectively.

$$U_{mean\_surface} = \frac{1}{n}\sum_{j=1}^{n} 1/\left(\frac{(T_{Sij} - T_{eaj})}{q_j} + R_{Si} + R_{Se}\right)$$

- *Equation 47.*, mean of ratios where internal surface temperatures are used or,

$$U_{mean\_air} = \frac{1}{n}\sum_{j=1}^{n} 1/\frac{(T_{iaj} - T_{eaj})}{q_j}$$

- *Equation 48.*, mean of ratios where internal air temperatures are used, where $U_{mean\_surface}$ and U_{mean_air} are the U-values obtained from internal surface and internal air temperatures respectively; T_{Si} is the surface temperature of the floor in the room; R_{Si} is the internal surface thermal resistance, taken to be 0.17 m^2KW^{-1} in accordance with BSI (2007), while R_{Se} is set to zero if external air temperatures (T_{ea}) are used, as is the case in this study. T_{ia} is the internal air temperature and q (Wm^{-2}) is the heat-flux density, derived from *Equation 39*. Index *j* identifies individual measurements and *n* is the number of measurements.

Justification for the proposed error estimation and propagation method

Table 9. gives a summary of the included errors.

<table>
<tr><th>Instrument error (Intrinsic)</th><th>Measuring condition/equipment set-up errors (Extrinsic)</th><th>Inherent property (not a measurement error)</th></tr>
<tr><td rowspan="3">± 5% Accuracy heat-flux and temperature sensors</td><td>±3% Operational/deflection error</td><td rowspan="3">±sd (% Natural variability U)</td></tr>
<tr><td>±5% Contact error</td></tr>
<tr><td>±5% Temperature location measurement error</td></tr>
<tr><td>Total error</td><td colspan="2">$\sqrt{5^2+3^2+5^2+5^2+sd^2}$ - Equation 49. and is the total estimated uncertainty for each individual location point measured in the environmental chamber; where sd is the natural variability of the daily or hourly U-value and sd is based on daily data for field data and hourly data for steady-state data collected</td></tr>
</table>

Table 9. Summary of proposed estimated measurement uncertainties; intrinsic and extrinsic errors obtained from ISO-9869, see Section 3.3.4.1.

In the proposed error estimation analysis, the natural variability of the mean U-value is represented by one standard deviation *(sd)* of hourly obtained U-values for an environmental chamber and daily data for in-situ field data as per *Equation 49.* below and is justified as follows:

1. **For field measurements**, daily U-values were used to estimate the final mean U-value over the monitoring period, with the *sd* of the daily values as an estimate of the natural variability in U between each day over the monitoring period. Daily data is used as suspended timber ground floor structures might typically be subject to a 24 hr periodic day/night cycle as suggested by Isaacs (1985b), though it is unclear whether this is really the case and what the short-term or (long-term) seasonal thermal mass time-lag of suspended ground floors is. Others have also used daily averaged U-values for field studies, e.g. Wingfield (2009) and Wingfield (2010a) for masonry and timber-framed cavity wall studies (without declared error analysis).
2. **Mean of ratios**: the proposed error propagation technique needs to be applied to the mean of ratios as per *Equation 47. or Equation 48.* and not the summation technique (or ratio of means) for reasons set out in Section 3.3 and 3.3.5.2. In the proposed technique, each day is treated as an independent datapoint. Given that environmental conditions do not vary at random but in a gradual and correlated way through time, each datapoint is an average that captures a daily time interval and the environmental variation associated with it. This approach is likely to minimise autocorrelation effects.

3. **For thermal chambers**, in the absence of 24-hour day/night or heating pattern cycles, smaller than 24hr time intervals could be used. However, time intervals which are too small may contain a lot of noise caused by researcher influence (e.g. opening/closing doors, touching of sensors during data collection) and might also show the cycling of the thermostat to provide the required heat input (Isaacs, 1985a). Hence some kind of averaging of the raw data (collected usually at 1- 5 minute intervals) over a longer time period may be useful to get a better estimate of the natural variability with other influences averaged out over a longer time period; for this reason a one-hour interval was used. Chapters 4.3.5. and 5.2.4. compare the mean U-value estimated from raw data (at 1 to 5 minute intervals) with the mean U-value of the hourly or daily data, which were very close and hence were good approximations of the estimated mean U-values for the case-studies used.
4. **Moving average techniques** were excluded here due to lack of independence of data and due to biasing the natural variation component low - as discussed in Section 3.3.4.2., section B.
5. The ***sd*** is a property of the distribution of the in-situ measured U-values, which reflects the spread of the data around the mean. Because the monitoring period is over a snapshot in time, using the *sd* provides a good estimate of the intrinsic variability observed in the observed data over the monitoring period, and would not need any further adjustment.
6. **Where surface temperatures are used for U-value estimation**, it could be argued that the ±5% temperature sensor location error (see *Table 8.)* does not apply. However in this research, external air temperatures were used, as discussed in Section 3.3.3.3. Additionally, where surface temperature are used, uncertainty is created by the addition of a constant R_{Si} in the final U-value estimates (see 3.3.3.2.). Hence some allowance for uncertainty around temperature measurements seems appropriate and this temperature location measurement error has been retained, though it's actual effect is unknown.
7. Like the other error propagation methods, the method proposed here also does not account for any variation in U due to longer-term seasonal changes unless measured over a longer time period including different seasons. The same assumptions about independent errors and normally distributed data is applied here as in all other methods, though further research would be required to investigate these assumptions; these issues are beyond the scope of this thesis research.

Error propagation: Combining intrinsic and extrinsic errors with natural variability of U in the quadratic sum

Given that buildings exist in a changing environment, it could be argued that the natural variation in in-situ measured U-values is a property of a dynamic U-value and should not be combined with true sources of error such as instrument and measurement condition errors. However, the natural variability of U over time as a result of changing environmental conditions is treated as an 'error' by ISO-9869 and Baker (2011b) in the estimation of a static U-value and by combining the natural variability with the other errors in the quadratic sum - see *Equation 41*. and *Equation 43*. respectively. The natural variability is not ideally combined with the true sources of error in the quadratic sum[10] as it is not a true source of error. While all intrinsic and extrinsic sources of error could be combined in the quadratic sum and the natural variability estimate could be reported separately alongside, this would make comparisons between U-values difficult (e.g. U_{mean} $\pm d_{x(intrinsic\ \&\ extrinsic\ errors)}$ $\pm$*natural variability*).

Hence for the purpose of this thesis and after ISO-9869 and Baker (2011), the true sources of error were combined in the quadratic sum with the natural variability as per *Equation 49.* Doing so allowed the presentation of a final estimate of uncertainty around the mean estimated U-value which better enabled comparison between different point U-values on the floor, pre/post intervention comparisons and estimating whole floor U-values from point-U-values.

A limitation of this technique is that underestimations of the uncertainty in U might occur due to use of the quadratic sum. There might be some compensation for this as some ISO-9869 assumed errors appear conservatively estimated compared to other estimates - see *Appendix 3.D.*; there might also be some double-counting as some errors cannot be separated from the *sd* - though whether this is the case and the actual extent of the errors remains unknown. Implications of this proposed error propagation technique are that for all the data, the errors will be minimum ±9%, based on the inherent instrument and measurement errors in *Table 9.*, with an addition of the *sd* as a representation of the natural variation of the daily or hourly U-values as per *Equation 49.* With some exceptions, uncertainty estimates in this thesis generally fell between Bales' (1985, p4.) error estimate range of ±5% to ±20% for in-situ field measurements - see Chapters 4, 5 and 6.

[10] Nor should the natural variability of U be combined in the simple addition of the individual errors as this would bias the uncertainty high because these are independent phenomena.

There are also situations where not all of the above individual estimated error components are required, for example when estimating differences or the impact of changes for the same sensor locations and these conditions are set out below and in *Equation 50.*

Point U-value comparisons between interventions

For comparison between U-value points on a floor (in the same intervention and between different floors), all of the above errors set out in *Equation 49.* and in *Table 9.* apply. However where identical instruments and measurement conditions occur (such as a sensor with the same fixing and location and use of the same sensors in the same location when pre/post intervention), contact, deflection and instrument errors need not be included to facilitate comparison of relative differences between the same locations on the floor – see *Equation 50.* The temperature location measurement error has been retained in all cases: even where temperature sensors remained in the same place: the intervention in itself might have had an effect on observed temperatures.

$\sqrt{5^2 + sd^2}$ - *Equation 50.* is the total estimated uncertainty where a relative comparison is made for the same point location; the first term is the error estimated from temperature location measurement errors; *sd* is based on daily data for field data and hourly data for steady-state data collected

Whole floor U-value comparisons

Obtaining whole floor U-value estimates from observed point U-values leads to uncertainties and these are identified below:

(1.) **Errors in each point measurement** will influence the whole floor estimated value and can be accounted for by summing the 'average' or 'weighted' individual errors according to the adopted 'whole floor' U-value estimation technique - see Chapter 4.4.2.

(2.) **Natural variation of U in each point** can be accounted for by inclusion of *sd* for each U-value point in the final uncertainty estimate and adjusted as described in (1.) but with the same limitations as noted prior.

(3.) **Spatial uncertainties:**

- Spatial variation with regards to the location and number of sensors (i.e. resolution) are an unknown but expected uncertainty arising from the spatial variation of heat-flow across the floor.

These can be minimised for by taking as many point measurements as possible and use of thermal images in sensor placement as noted in Sections 3.3.2., 3.2.6.1. and Chapter 4.4.2.

- There will be an unknown uncertainty in estimating techniques of the whole floor U-value; this can be minimised with use of thermal imaging to ensure appropriate point U-value averaging or weighting techniques - see Chapter 4.4.2.

For comparison between whole floor U-values, only the first 2 sources of uncertainty (error in each point measurement and variability in U) can be included and can be weighted for each individual point U-value in the final estimated uncertainty of the whole floor U-value, as illustrated in Chapter 4.4.2. The spatial uncertainties cannot be quantified and can only be minimised for by careful research design. Unknown uncertainties will be associated with the above error estimates and assumptions, use of surface temperature sensors (and R_{Si} addition) and spatial and natural variations and whole floor averaging techniques, which would affect confidence in final estimated whole floor U-values. Transparency is required in communication of results and where comparisons are undertaken, as discussed in the following section.

3.3.4.4. Presentation of results and errors

Great care is required to avoid erroneous conclusions from comparisons between different in-situ measurement sources and with in-situ measured and modelled U-values, hence presentation of results alongside their estimated error is important.

The main in-situ U-value standards (see Section 3.3.) set out in-situ data U-value measurement reporting recommendations, including: transparency about sensor locations and specifications, environmental conditions and analysis technique and discussion of likely sources of uncertainty and error estimation methods. In-situ estimated U-values should be presented as $U \pm d_x$ where d_x is the fractional or absolute measurement uncertainty, reflecting that an uncertainty remains present in the final result (JCGM, 2009). Doing so allows for a more robust comparison to other measurements, published literature, specifications and standards JCGM (2009, Taylor, 1997) and models and pre/post intervention studies. However, erroneous judgments of divergence between different sources could be made because of the uncertainties surrounding the U-value, which might have been obtained in different ways.

Hence (JCGM, 2008) advocates an entirely transparent approach in the expression of uncertainties with a detailed presentation of how the uncertainty was obtained so as to allow for comparison of results and judge reliability of the final estimated values.

At present, many reported U-values estimated from in-situ measurements lack uncertainty contextualisation and research design and analysis transparency, see e.g. Rye (2012), Byrne (2013) and Cox-Smith (2008), limiting the wider value of the reported results. The significance of results can only be appreciated when presenting U-values with error margins and this supports appropriate policy and decision-making. For example if policies or decision-making are based on a range of estimated U-values ($U \pm d_x$), this allows the policy-maker, assessor and building owner to assess the uncertainty associated with the intervention and to consider worst-case and best-case payback scenarios based on these ranges, which is not possible when only a U-value is reported without error margins.

3.3.5. Instrument calibration

Heat-flux sensors should be re-calibrated every two years according to specific criteria (BSI, 2014, Hukseflux, 2006). Calibration of all measuring instruments should be undertaken to test whether any of the measuring instruments used have drifted outside their stated accuracies. Normally calibration involves testing instruments in a hot-box controlled environment where they measure a known quantity and each instrument is then compared to how close the measurement matches this known quantity. When calibrating sensors, measuring conditions should be as close as possible to the actual measuring conditions (Bales, 1985).

Instead of a hot-box calibration, side by side 'calibration' testing of sensors could also be undertaken as described by Doran (2008); re-calibration could also be done by placing sensors on top of each other as described by Hukseflux (2006). For this PhD study, most sensors were <2 years old, but where possible, side-by side checking of some of the sensors was carried out for research undertaken in Chapter 4, though limited time and resources prevented heat-flux instrument calibration used in Chapter 5 and 6. Several of the sensors used for the studies reported in Chapters 5 and 6 were <2 years old or previously checked 'side by side', however some older sensors were used without checks - this research limitation means that sensor drift cannot be excluded.

3.4. Part 3: Data collection

This section briefly presents the research hypotheses, primary field data collection, sampling strategies, use of exploratory studies, research ethics and generalisability of the research. Detailed research design related to different studies undertaken is set out in Chapter 4, 5 and 6. This thesis is structured around two main studies (STUDY 2 and 4), with exploratory studies (STUDY 1 and 3) informing the main field study research design - see *Table 10.* below. Specifically, the monitoring of floor heat-flow in a pilot study and in an environmental chamber (STUDY 1 + 2) are set out in Chapter 4. STUDY 4 is split in two parts over Chapters 5 and 6, with Chapter 5 presenting the uninsulated floor study, while Chapter 6 presents the impact of two different insulation interventions and the short-term intervention impact on thermal comfort and lessons learned from a short pilot study (STUDY 3).

<table>
<tr><th>STUDY 1
Field study
London</th><th colspan="2">STUDY 2
Salford EH</th><th colspan="2">STUDY 3
Pre-post pilot Manchester</th><th colspan="5">STUDY 4 (A & B)
Field study Ealing</th></tr>
<tr><td>Pilot study (2012)</td><td colspan="2">Initial study (2013)</td><td colspan="2">Pilot study: pre-post insulation intervention study (2013)</td><td colspan="5">Field study: pre-post insulation intervention study (2013-2014)</td></tr>
<tr><td rowspan="2">Field study, London occupied house; low-resolution monitoring: 2 locations on floor</td><td colspan="2" rowspan="2">Salford Energy House, environmental chamber; high resolution monitoring: 15 locations on floor</td><td colspan="2" rowspan="2">Manchester region, unoccupied house ; low-resolution monitoring: 4 locations on floor</td><td colspan="5">West London, unoccupied house; high resolution monitoring: 27 locations on floor. Additional monitoring of environmental variables, as well as monitoring of airtightness, floor void and thermal comfort variables pre-post interventions.</td></tr>
<tr><td colspan="2">STUDY 4 A
Field study Ealing (pre-insulation)</td><td colspan="3">STUDY 4 B
Field study Ealing (post-insulation)</td></tr>
<tr><td>Uninsulated</td><td colspan="2">Uninsulated</td><td>Uninsulated (pre)</td><td>Insulated (post)</td><td colspan="2">Uninsulated floor (pre)</td><td>EPS bead insulated floor (post)</td><td colspan="2">Woodfibre insulated floor (post)</td></tr>
<tr><td>Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td colspan="2">Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td>Sealed airbricks</td></tr>
<tr><td>March 2012- April 2012</td><td colspan="2">May 2013</td><td>September 2013</td><td>October 2013</td><td colspan="2">January 2014</td><td>End of January 2014-mid-February 2014</td><td>February-March 2014</td><td>mid-March 2014</td></tr>
<tr><td>Chapter 4</td><td colspan="2">Chapter 4</td><td colspan="2">Chapter 3 & 6/Appendix</td><td colspan="2">Chapter 5</td><td colspan="3">Chapter 6</td></tr>
</table>

Table 10. Summary table of the different studies undertaken.

3.4.1. Research areas and hypotheses

From the research questions identified in Chapter 2.9. and after Barker Bausell (1994), six hypotheses were constructed - as summarised in *Table 11.* and in more detail in *Appendix 3.B.* The hypotheses draw on physical theory; establishing hypotheses is an important part of designing planned interventions to clarify causal relationships (Glass, 2008). Statistical tests support hypothesis testing: statistically significant differences are important to meaningful experimental design (Barker Bausell, 1994) and from which trends, patterns and findings can be "*the basis for generalisation*" (Robson, 2011).

Hypotheses (H)	**Research design considerations**
H1. There will be a large observed spread of Up-values across the uninsulated floor.	Measure heat-flow in different locations on the floor; undertake high-resolution heat-flow monitoring of floors; unoccupied house or thermal lab to enable high-resolution monitoring - See Chapters 4 and 5.
H2. There will be increased perimeter Up-values observed compared to locations further away from the external wall (i.e. the non-perimeter zone). ***H2a. This will be observed both for insulated and uninsulated floors, albeit reduced for the latter.***	As above - See Chapters 4 and 5. H2a: See Chapter 6
H3. There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks. ***H3a. and this effect will be proportionally smaller in insulated than in un-insulated floors.***	Undertake airbrick sealing experiments; measure environmental variables to qualitatively assess changing influencing variables over time between observations - See Chapter 4 and 5. H3a: See Chapter 6
H4. There will be a reduced spread of Up-values observed for the insulated floor compared to the uninsulated floor	Undertake high-resolution monitoring of a floor in the same location pre/post intervention. Measure additional environmental variables to qualitatively understand/identify any confounding factors between pre/post comparisons; control heating pattern and minimise occupant influence or measure in an unoccupied house - See Chapter 6
H5. There will be a significant decrease observed in thermal transmittance after insulation installation. ***H5a. insulation will also be observed to improve dwelling airtightness***	As above + undertake blower door tests in each intervention period to understand the effect of each intervention on air leakage - see Chapter 6.
H6. Post-insulation it will be observed that thermal comfort is improved.	Thermal comfort studies typically include occupant surveys; however, if this is not possible, room air temperature measurements in several locations in the room pre-and post-intervention might highlight impact of interventions for comparison with theoretical comfort thresholds. Measure additional environmental variables. See Chapter 6.5.

Table 11. Summary table of testable hypotheses.

A thermal chamber and an unoccupied house were identified as the best strategy to test these hypotheses, enabling high resolution floor heat-flow measurement and undertaking of interventions with internally controlled conditions which would not be possible in occupied houses. A summary table of the pro's and cons of (un)occupied houses and use of a thermal lab are set out *in Appendix 3.E.* To test hypotheses H2a and H3 to H6, an 'interrupted time series design' was undertaken (Robson, 2011): floor heat-flow was measured prior to floor interventions, with continued floor heat-flow measurements after intervention, "*offering a unique perspective on the evaluation of intervention (or "treatment") effects.*" (Glass, 2008).

3.4.2. Sampling case studies

Following on from the research questions, objectives and hypotheses, five distinct primary data collection areas were identified:

1. High resolution heat-flow measurements in a thermal chamber under controlled conditions to characterise floor heat-flow and test floor heat transfer theory such as increased heat-flow in the perimeter versus the non-perimeter zone; with airbricks open or closed and to test how representative single (or a few) point measurements are of the whole floor. Research design and limitations are discussed in Chapter 4; discussion about generalisability in Section 3.4.4.

2. High resolution heat-flow measurements in the field to characterise in-situ heat-flow in an actual case-study to test and compare theory from the thermal chamber and to build theory with a pre/post insulation study. Measurement of environmental variables will be important to understand pre/post comparison studies due to confounding factors. Research design and limitations are discussed in Chapter 5 and 6; generalisability is discussed in Section 3.4.4.

3. Monitoring of floor void conditions in the field to compare floor void conditions with literature values; research design and limitations are discussed in Chapter 5.

4. Data collection for thermal comfort evaluation in order to test thermal comfort theory and to build theory with regards to the conditions of insulated and uninsulated floors. Research design and limitations are discussed in Chapter 6.

5. Blower door tests to evaluate air leakage of pre- and post intervention measures.

3.4.2.1. Primary data collection sampling

Primary data for all five data collection areas were collected by taking a multiple case-study approach. Prior to undertaking the main research data collection, exploratory studies were first undertaken to inform the main studies - these are described in Section 3.4.2.2.

Due to the disruptive and seasonal nature of the data collection and the limited timescale and resources of this PhD research, random sampling of a large number of floors - whether for monitoring floor heat-flow, thermal comfort or floor void conditions - was not possible. Purposive sampling to generate additional or new observations (Robson, 2011), i.e. to maximise understanding and learning (Stake, 1995), was instead undertaken as a sampling strategy for all of the main primary data collection case-study sampling strategies. Convenience sampling is a typical sampling strategy for exploratory studies (Robson, 2011), as also undertaken in this thesis research for both exploratory studies (STUDY 1 and 3), i.e. measurements were taken where the author had access to an available house.

For floor heat-flux monitoring, purposive sampling allowed the selection of cases which fulfilled the needs and objectives of the research purpose (Robson, 2011, Saunders, 2009). For example, STUDY 2, (Chapter 4) was an environmental chamber replicating an actual dwelling and floor construction and allowed the study of floor heat-flow in controlled conditions and at high-resolution. Additionally, heat-flow monitoring in STUDY 4 (Chapter 5 and 6) took place in an unoccupied house over an entire winter season and allowed high-resolution heat-flow monitoring pre/post intervention studies with homeowner approval - see summary in *Table 12*. The implications of these non-random case-study sampling techniques on generalisability of results is discussed in Section 3.4.4.

Primary data collection (as per 3.4.2.)	**Sampling strategies and considerations**
1. High resolution heat-flow measurements in a thermal chamber	**The Salford Energy House (EH) was selected purposively** for the initial floor heat-flow study - see Chapter 4 for research design. The Salford EH is a reconstructed 1919 dwelling in an environmental chamber, allowing for the control of both internal and 'external' environmental conditions during the study and high-resolution monitoring on the floor as the chamber is unoccupied. Other considered options included the construction of a test-cell in a thermal chamber such as done by Harris (1997), however access to a suitable thermal lab for this purpose was not obtained during this study.
2. High resolution heat-flow measurements in the field 3. Monitoring of floor void conditions 4. Data collection for thermal comfort evaluation 5. Blower door tests	**The pre/post insulation study in the field was selected purposively** and was based on: availability of the house over the winter heating season in 2013-14; being unoccupied over this period; access to the floor void; permission and agreement with the home-owner to undertake high-resolution measurements and pre/post insulation studies. Reduced distance to the author's place of residence was also an important consideration for easy access and regular data collection.

Table 12. Sampling strategies and considerations for the main studies.

Detailed research design and data collection methods for each case-study are discussed in each relevant chapter.

3.4.2.2. Exploratory studies

As suggested by Barker Bausell (1994) and Robson (2011) at least one pilot study was conducted to test methods used and feasibility of the main proposed study and its research design and approach. Convenience sampling was used for all the explorative study sampling; these case-studies informed the purposive sampling of cases and research design of the main research studies and exposed in-situ monitoring difficulties - see Chapters 4, 5 and 6. The exploratory studies highlighted the difficulties with in-situ floor heat-flux monitoring in an occupied house, including high-resolution measurement, void access, occupant influence, heating control and monitoring in a changing external environment. Two brief exploratory studies were undertaken:

1. A low resolution heat-flow monitoring study (STUDY 1) as part of the author's 2012 MRes study; as described in Chapter 4.2. Lessons learned lead to a high-resolution measurement study in an environmental chamber (STUDY 2) to allow for heating control, minimise occupant and external weather influence and undertake high resolution measurement.

2. A low resolution pre/post intervention heat-flow study (STUDY 3) in September/October 2013; lessons learned are described in Chapter 6.2. and *Appendix.6.A.* and directly informed the main pre/post intervention field study in West-London (STUDY 4).

3.4.3. Ethical concerns

There are several ethical issues related to the monitoring of occupied buildings, documented by e.g. Eberhardt (1991), Gupta (2010) and Leaman (2004, 2010). However these sources mostly focus on monitoring of occupants' behaviour in buildings, including their own homes, which does not apply to this thesis research. Monitoring and accessing people's private properties poses questions about professional conduct, research ethics and personal safety, especially when also accessing confined floor void spaces. Specific ethical concerns relevant here are listed in *Table 13.* alongside how to address these concerns.

Ethical concerns	How to address these concerns?
privacy, confidentiality	Information sheets and informed consent forms (see example in *Appendix 3.F*. and *5.A.*) to clearly state voluntary involvement and confidentiality of data collected; no pictures of personal data to be collected; participant can at any time withdraw and access any information held. Safety issues discussed further below.
Access and disruption/impact on occupants	• More disruptive work (such as high resolution heat-flow monitoring) to be undertaken in unoccupied houses. • Minimise disruption by data collection only when needed; state when and for what access is required; confirm appointments and arrive on time.
Duty of care, trustworthiness	There is also a duty of care by the researcher when finding any issues (for example timber rot in the floor) and notifying the participant; likewise when gaining access to an unoccupied property without the owner present. This was addressed through informed consents and regular communication with the owner and a disclaimer that the author is no expert surveyor. See Informed Consent and information sample letters in *Appendix 3.F*. and *5.A*.
Security and safety	Risk assessments were set up for field work such as lone working and for ensuring safe site conduct and equipment handling - e.g. PAT testing electrical heaters. Accessing and working in confined spaces such as floor voids required extra health and safety and personal safety considerations when entering floor voids - see Health and Safety risk assessment in *Appendix 5.A*. This included provisions when entering confined spaces with potentially hazardous air quality for the researcher; and use of the department's 'buddy scheme', where two individuals agreed to raise alarm if the researcher had not been in touch at an agreed time.

Table 13. Summary table of research ethics and how to address these

3.4.4. Generalisability of research findings

External validity or generalisability of research outcomes

As described in the previous section, for this thesis research, cases were non-randomly sampled, hence seeking statistical significance of results in the wider population, obtained from a small sample and non-randomly sampled case-studies, is not possible (Silverman, 2010, Robson, 2011, Saunders, 2009, Flyvbjerg, 2006) neither a purpose of this thesis research. However, purposively selected case-studies were selected based on maximising understanding and learning and can give meaningful and detailed insights and refinements for the testing and building of methodology and theory, which can be transferable and useful to the wider population where applied in similar conditions and with similar purpose (Silverman, 2010, Flyvbjerg, 2006, Stake, 1995). Generalisability beyond the case studied does not need to be based on statistical inferences (Robson, 2011) and "*may be thought of as the development of theory which helps in understanding other cases or situations*" (Robson, 2011) and any trends, patterns and findings "*are the basis for generalisation*" (Robson, 2011). Case-studies can also highlight observed phenomena and lead to refinement or modification of pre-existing generalisations (Stake, 1995). This was done by for example Lowe (2007) who demonstrated the presence of a thermal bypass in millions of cavity-walls based on a single case-study. Indeed, findings based on purposive case-study data collection may lead to generalisations to inform more about typical case-studies (Saunders, 2009) and may support the refinement and modification of models and theories (Stake, 1995), which might also apply in other cases with similar characteristics. Case-studies could also highlight interesting findings about research methods and efficacy of proposed interventions (Silverman, 2010), which may be applicable elsewhere and support future research. Finally, case-studies can also be useful to highlight certain trends in the data collected (Robson, 2011) and to generate and test hypotheses (Flyvbjerg, 2006), as undertaken in this thesis. Hence while findings are specific to the particular case-studies and not representative of the wider population, they may highlight methodological and theory implications as well as highlight generalisable trends and patterns and will inform future research and support future studies.

The high-resolution heat-flow measurements undertaken in the Salford Energy House environmental chamber (STUDY 2, Chapter 4), are not representative of the wider pre-1919 housing population. Additionally, and as discussed in Section 4.3., the Salford EH has been reconstructed in an environmental chamber and there are several variables which are not replicated from an actual house.

With regards to the field study (STUDY 4, Chapters 5 and 6), the experimental research design was designed to be as representative as possible of an occupied dwelling, for example by replicating occupied dwelling heating patterns. However, each research design has limitations, such as not replicating the effect of uninsulated radiator pipes in the void, taking measurements in an unfurnished room, etc. Additionally, the field study house is almost certainly not representative of the entire pre-1919 housing stock in the UK. In particular, the field study had over-site concrete, 3 sleeper walls with limited openings in between floor void sections; the airbricks were located within the joist spacings and the total ground floor area was small. This study conducted cross-sectional, not longitudinal work due to access limitations, hence this research excludes trends over time. More dwellings need to be studied to assess the effect of differences in the housing stock and to understand if any observed trends exist for floors with different characteristics and over a longer time-period. Despite the above caveats, several of the research findings were transferable and applicable to the wider population. A summary of the issues are described in *Table 14.* below.

Internal validity refers to replicability and to the accuracy of the findings and whether they capture their intended target and in the case of interventions, whether findings are due to the chosen intervention (i.e. causation) and not due to other influences (Robson, 2011). To support internal validity, hypotheses were tested and confounding variables were controlled where possible (such as heating schedule, using the same sensors in the same locations between interventions, minimising researcher and occupant influences etc.). Additionally, a detailed field diary was made and research design is reported transparently and in-depth.

General concerns	How to address these concerns?
Replicability of research (Internal validity)	Hypotheses testing; control confounding variables as much as possible (such as heating schedule, sensor replacement between interventions, etc.), other independent variables were measured to qualitatively assess the impact of changing environmental conditions on observed heat-flow. Additionally, the research method and data collection procedures were noted in a detailed field diary during the monitoring process; regular (digital) archiving of field notes was undertaken. Calibration checks were undertaken where possible. Research design is transparent and reported in-depth.
Generalisability outcomes (External validity)	The purposive case-study approach cannot provide population-wide inference (Saunders, 2009) but was used to generate and test hypotheses (Flyvbjerg, 2006), from which trends, patterns and findings can be "*the basis for generalisation*" (Robson, 2011) and which can be transferable and useful to the wider population where applied in similar conditions and with similar purpose (Silverman, 2010, Flyvbjerg, 2006, Stake, 1995).

Table 14. Summary table of general concerns and how to address these

3.5. Summary

This chapter introduced in-situ U-value measuring and analysis techniques and associated uncertainties in detail, alongside raising conceptual issues of measurement location and difficulties of low resolution heat-flux point measurements as a comparison to whole floor U-value models. These issues are further explored in the following chapter, based on in-situ measurements in the Salford Energy House. This chapter also set out the main studies and sampling strategies conducted in this thesis research and associated ethical and general concerns, including generalisability of findings based on case-study research.

Chapter 4: Initial uninsulated floor heat-flow studies

4.1. Introduction

This chapter aims to clarify and develop the identified conceptual floor heat-flow measuring issues as identified in the previous chapter, while also contributing to a better understanding of the actual U-value of floors and comparison with models - all of these areas were identified as being poorly characterised at present. This chapter primarily addresses research question 1 ("*How should in-situ suspended timber ground floor U-values be estimated?),* while also addressing research question 2 *("What is the in-situ measured thermal transmittance of floors and how does it compare to model predictions?").*

Primarily, this chapter presents and discusses the high-resolution in-situ measured U-values of 15 point locations on the floor in the Salford Energy House (EH), (STUDY 2). Given the issues surrounding measurement uncertainty and research design as set out in Chapter 3.3, a section in this chapter is also devoted to these issues. The Salford EH research design was informed by results from additional data analysis of the author's 2012 in-situ floor U-value monitoring pilot study in the field (STUDY 1). Hence the 2012 pilot study data and its re-analysis for this PhD research is the opening section of this chapter, followed by the main Salford EH floor U-value study under controlled conditions.

The Salford EH high-resolution study[1] enabled testing of whole floor U-value averaging techniques to enable comparison to predicted values and are described in Section 4.4.2 and 4.4.3 respectively. Additionally, the impact of sensor locations on estimated results is discussed alongside the impact of closing of airbricks on U-values in Section 4.4.5. and 4.4.4. respectively.

The diagram below gives an overview of the studies subject to this chapter's analysis and discussion, STUDY 1 and 2 are highlighted in red.

[1] I.e. many points on the floor surface observed.

<table>
<tr><th>STUDY 1
Field study London</th><th colspan="2">STUDY 2
Salford EH</th><th colspan="2">STUDY 3
Pre-post pilot Manchester</th><th colspan="5">STUDY 4 (A & B)
Field study Ealing</th></tr>
<tr><td>Pilot study (2012)</td><td colspan="2">Initial study (2013)</td><td colspan="2">Pilot study: pre-post insulation intervention study (2013)</td><td colspan="5">Field study: pre-post insulation intervention study (2013-2014)</td></tr>
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Field study Ealing (post-insulation)</td></tr>
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<tr><td>Chapter 4</td><td colspan="2">Chapter 4</td><td colspan="2">Chapter 3 & 6/Appendix</td><td colspan="2">Chapter 5</td><td colspan="3">Chapter 6</td></tr>
</table>

Table 15. Summary table highlighting the studies subject of this chapter.

4.2. Re-analysis of the 2012 Pilot Study (STUDY 1)

Heat-flow of an uninsulated suspended timber ground floor was monitored in 2012 in a pre-1919 terraced house in North London (see Pelsmakers (2012)), similar to other low-resolution floor measurements by e.g. Baker (2011a), Currie (2013), Miles-Shenton (2011) and Stinson (2012) in the UK and Isaacs (1985b) in New Zealand. This data was re-analysed as described in the following sections.

4.2.1. Research Design

The specifics of the research design of this 2012 pilot study (such as sensor fixing methods) are described in more detail in Section 4.3.2 (page 152) and 4.3.4 (page 155) together with the Salford EH research design (Section 4.3.1., page 150). (See also *Appendix 3.F.* for consent form and information sheets).

The pilot-study house was selected from a convenience sample to gain easy access and minimise disruption to occupants given that sensors would be located on the floor. This pilot study was used to better understand in-situ floor U-value measuring and data analysis techniques.

4.2.2. Temperature measurements & data collection

Different in-situ floor U-value data monitoring can be undertaken (see Chapter 2.4.2.); U-value estimation from internal environment to void air temperatures was initially adopted for the 2012 pilot study analysis (see Pelsmakers (2012)), after Isaacs (1985b), Currie (2013) and Harris (1997, 1994).

However, as U-values are calculated from the inside to the outside environment (Szokolay, 2008) and given that ISO-13370 calculates the U-value of a suspended floor system to the outside environment (through the void (BSI, 2009b), see Chapter 2.3), use of external temperatures would enable comparison of in-situ estimated U-values with models and to understand the actual thermal performance of the floor system. Hence the use of external temperatures to estimate the U-value of a suspended floor system instead of void temperatures was undertaken for this PhD research.[2]

To enable comparison to models and to investigate the impact of using air- or surface temperatures on floor system U-value estimation, the 2012 pilot study data were re-analysed for the purpose of this PhD as follows:

a. Using the internal to external environment for in-situ U-value estimation.
b. Comparison between U-values estimated from internal surface temperatures versus skirting air temperatures which were also collected. Where surface temperatures were used, an assumed surface resistance (R_{Si}) of 0.17m^{2}KW^{-1} was added as per *Equation 47.*, explained in Chapter 3.3.
c. Daily U-value averages (*Equation 47.)* were determined with error analysis as described in Chapter 3.3.4.3 (p 124.) and in accordance with *Equation 49.*

Two HukseFlux HFP01 heat-flux sensors (±5%) were fixed in 2 locations: location 1 (U1) was measured in the perimeter zone (600 mm from an external wall and 1300 mm from another external wall and in line with the only air-brick location in the void below); location 2 (U2) was measured about 3500 mm away from any external wall, as per *Figure 14.* Surface temperature thermistors (±0.1°C) were located on top of the heat-flux sensor surfaces, after Baker (2011b); while air temperatures at skirting height were measured with HOBO-U12 sensors (±0.35°C).

---

2 Void and external air temperatures would be expected to be significantly different in the case of the floors subject to this research (which are enclosed by foundation walls with a limited number of airbricks present), unlike some of Isaacs' (1985b) sample.

Both heat-flux sensors and all of the thermistor air temperature sensors were connected to an Eltek Squirrel-1000 data-logger, which allowed remote data collection. External air temperatures (±0.5°C), were monitored in the back garden at 1800 mm high with a DAVIS Vantage Vue weather station.

Monitoring was undertaken over 30 days (though data loss reduced this to 23 days) between March 18th to April 9th 2012. Measuring floor heat-flow at high-resolution in occupied dwellings is problematic due to the floor surface being used for day-to day living purposes and resource availability.

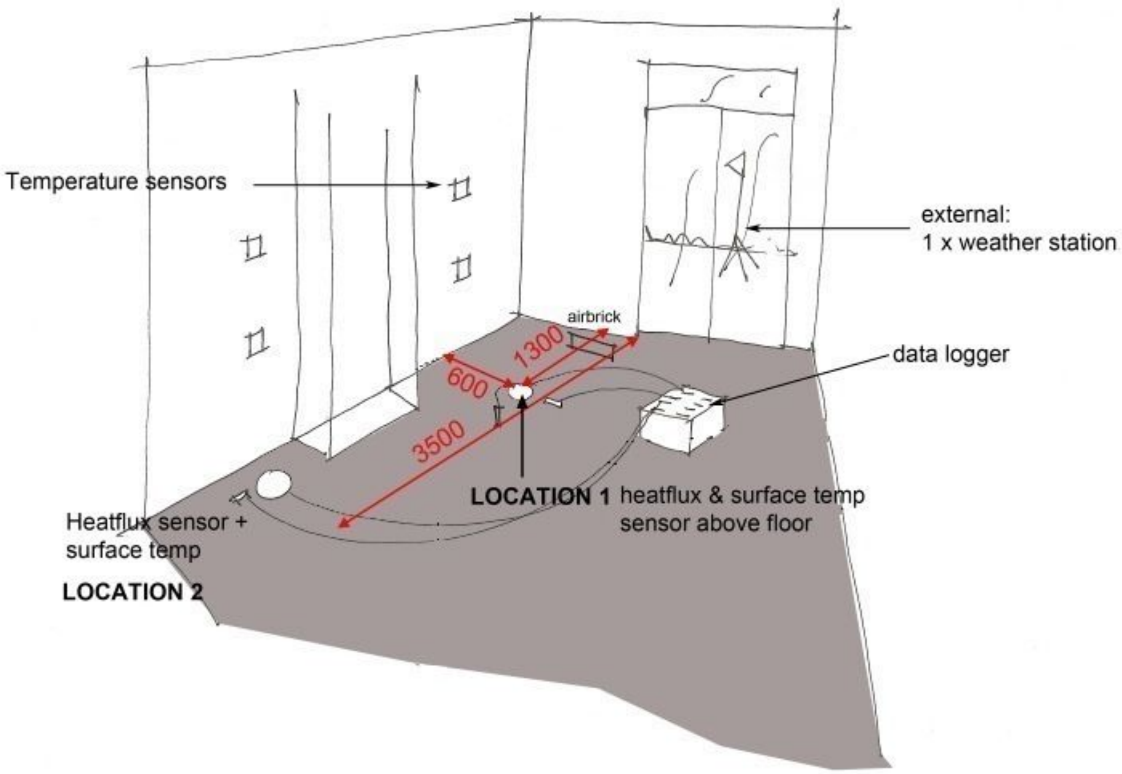

Figure 14. Diagram of instruments and measuring locations

While heat-flow was monitored for a longer period, the first ten days of data were used for analysis. This is because the ten day data met the ISO test criteria as described in Chapter 3.3.1, while the 23 day data did not. This is because the latter part of data logging coincided with unseasonally warm temperatures (MetOffice, 2012b, MetOffice, 2012a) and because from March 26th the occupant reduced space-heating from about 7pm to 12am, eventhough internal room air temperatures were on average <18°C during the day; reducing ΔT. Both events lead to a period of fluctuating heat-flow, however the contribution of the different variables to this is unknown due to the uncharacterised simultaneous interactions of warming external air temperatures, reduced heat-flow from internal spaces to the void and the thermal mass behaviour of the ground changing to a new equilibrium.

4.2.3. Pilot study results

Depending on the location of the temperature measurements (surface or skirting air temperatures), the estimated U-value in the perimeter location (U1) ranged from 1.72 ±0.31 $Wm^{-2}K^{-1}$ to 2.08 ± 0.44 $Wm^{-2}K^{-1}$; which is about twice that of location U2 which ranged between 0.88 ±0.14 $Wm^{-2}K^{-1}$ to 1.02 ± 0.18 $Wm^{-2}K^{-1}$; these values were outside the margins of measurement errors. U-values estimated from surface to external air temperature (see *Figure 15.)* were lower than those estimated from internal air temperatures measured at skirting height, although the U-values in the same locations (but determined with different temperatures) were within the estimated margins of error (error margins estimated as per *Equation 49.).*

Averaging the two surface to external air temperature point U-values gave an estimated U-value of 1.30 ±0.22 $Wm^{-2}K^{-1}$. However, given that one point was located in the perimeter zone,[3] which was only around 30% of the entire floor (see *Figure 14.)*, using the average as the whole floor U-value is likely to lead to an overestimation of the whole floor U-value by giving both observed locations equal weighting. Deriving the whole floor U-value from a weighted average based on a 30/70 perimeter/non-perimeter weighting, reduced the average floor U-value to 1.13 ±0.19 $Wm^{-2}K^{-1}$. Note that this excludes the presence of joists, which would lower the estimated in-situ U-value slightly for the uninsulated floor.

The ISO-13370 floor U-value model (BSI, 2009b) estimated a floor system U-value of 0.43 $Wm^{-2}K^{-1}$, based on the pilot study's house and floor characteristics, excluding joist presence *(see Table 21. Page 183)*. This modelled U-value is below the 0.55 $Wm^{-2}K^{-1}$ mean published U-value presented in Chapter 2.4. and just outside the literature range of 0.45 $Wm^{-2}K^{-1}$ to 0.70 $Wm^{-2}K^{-1}$ - see *Table 1*. This disparity might be due to the limited void ventilation (0.0011 m^2/m) and the small perimeter to floor area ratio (*P/A* = 0.24m/m^2) due to the deep plan of the pilot study house compared to the assumptions in the sources (typically *P/A* 0.30 m/m^2 and ventilation area 0.0015 to 0.0030 m^2/m).

From the results above, the average in-situ estimated floor U-value (1.30 ±0.22 $Wm^{-2}K^{-1}$) was more than twice as high as the modelled U-value, see *Figure 15.* However, the model might be an inaccurate representation of the actual U-value due to the input assumptions (see Chapter 2.3.).

[3] The perimeter zone was defined as within 1000mm from an external wall after Delsante (1989) see discussion in Section 4.4.1, page 162.

Even if the U-values are weighted for estimated perimeter/non perimeter zones, the estimated whole floor U-value (1.13 ±0.19 $Wm^{-2}K^{-1}$) is still more than double the model estimated value. This raises questions about the low-resolution pilot-study and that direct comparisons between modelled and in-situ measured U-values might not be meaningful: summarising whole floor U-values from a large surface by just a few measurement locations is unlikely to reflect the whole floor's thermal transmittance and hence makes comparison to models difficult; this is illustrated by *Figure 16.*

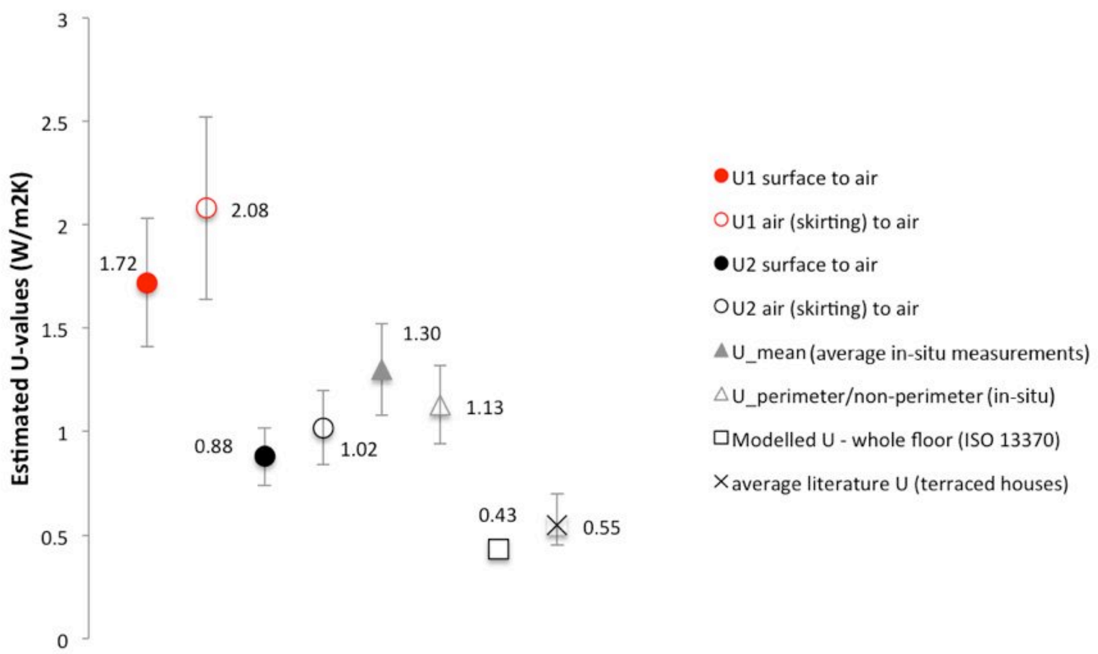

Figure 15. Presents estimated in-situ U-values in 2 locations for the 2012 pilot study (round data points) and compared to modelled (square datapoint) and literature average U-values for terraced houses (cross bar data point); outline data-points are in-situ estimated U-values from skirting air to external air, while solid data points used surface to external temperatures. The error margins were estimated as per Equation 49. for in-situ measurements, while for literature values error margins represent the minimum and maximum U-values found in publications. Models exclude joist and thermal bridging effects.

Figure 15. also highlights that:

- As expected, nearer the exposed perimeter, the observed point U-value (U1) was greater (almost twice as high).
- The addition of a large R_{Si} of 0.17m^2KW^{-1} where surface temperature data was used in accordance with *Equation 47.*, lead to lower estimated U-values compared to U-values estimated with skirting air temperatures; doing so had a proportionally smaller impact with lower U-values.

- There is a large variation of U_p-values depending on where the point measurements were undertaken (i.e. in the horizontal plane on the floor surface, due to exposure to external elements) and depending on which temperature data was used (i.e. measurements in the vertical plane due to stratification), though the latter U-values were within the estimated margins of error.

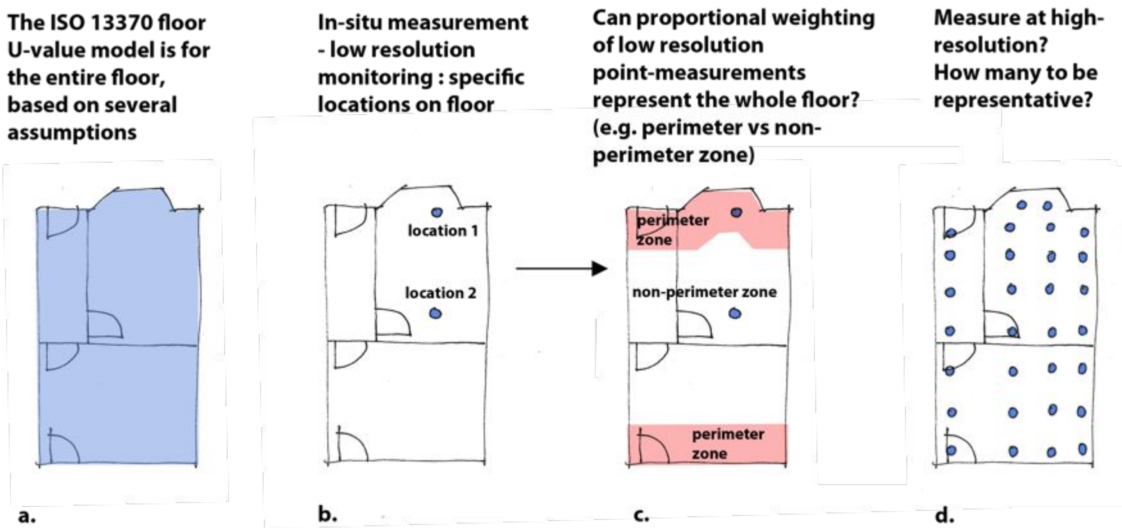

Figure 16. a., b., c. and d. highlight that a floor U-value model is for the whole floor (a.), while in-situ floor U-value measurements can be at low-resolution (b.), leading to an area representative weighting (c.), or at high-resolution (d.), covering a greater area of the floor, though with significant practical and resource constraints. This raises the question whether strategic and carefully distributed measurements could be representative of the U-value of the entire floor (as illustrated in c.), or whether an in-situ U-value can only be obtained from many point-measurements as illustrated in (d).

4.2.4. Summary, further research and hypotheses testing

The pilot study highlighted that different U-values were estimated depending on where and how variables were measured. In addition, low-resolution measurements might not be representative of the whole floor U-value and hence comparison to models could be misleading. The modelled and measured U-value difference was exacerbated by the large divergence between the two estimated point U-values, indicating a possible large spread of heat-flow across the rest of the floor (but not measured here). For walls, BRE (2014c) suggested that more than two heat-flux sensors on the wall are recommended to gain an understanding of the spatial distribution of U-values and *"would provide an indication of the level of confidence in U-values that are measured"*.

Finally, ten days of data collection appeared sufficient to obtain valid U-values[4] from the field, though short-term monitoring cannot isolate the impact of seasonal effects.

Questions that arise from this pilot study are:

- In which internal/external vertical plane do we measure 'representative' temperatures used for U-value determination?
- How to derive whole floor U-values from point U-value measurements?

These questions were further investigated in the Salford EH to further refine and develop in-situ floor measuring methods, and specifically to:

- investigate the impact of temperature sensor location on U-value estimation by measurement of both internal surface temperatures and internal air temperatures;
- control the internal and external environments and diminished occupant influence - this should lead to reduced measurement uncertainties;
- undertake measurements on a joist to adjust whole floor U-value estimates to take account of the joist presence;
- undertake high-resolution heat-flow monitoring to understand the spread of U_p-values across the floor; this will enable investigation of sensor placement location and measurement techniques as well as to investigate whole floor averaging techniques to enable a more robust comparison between models and in-situ estimated U-values;
- to test the following hypotheses (H) as set out in Chapter 3.4.1.:
    - H1. *"There will be a large observed spread of U_p-values across the uninsulated floor."*
    - H2. *"There will be increased perimeter U_p-values observed compared to locations further away from the external wall (i.e. the non-perimeter zone)."*
    - H3. *"There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks."*

[4] "valid' U-values as defined in Chapter 3.3.1. by the data meeting the three ISO-9869 test criteria; though for further analysis, ISO-9869 was not used - see Chapter 3.3.

4.3. The Salford Environmental Chamber: research design (STUDY 2)

The Salford EH is a semi-detached, two-bedroom reconstructed house in an environmental chamber at the University of Salford and was available for 10 days in May 2013 to measure floor heat-flow at high resolution (i.e. on 15 locations on the floor, one of which was a joist location) in a controlled environment. The purpose of this high-resolution study was to test hypotheses (see Section 4.2.4.) and generate new knowledge. In particular, this study aimed to:

- understand the spread of heat-flow across the floor and test whether a perimeter effect was present as per solid ground floor theory (see Chapter 2.2.).
- test and understand the impact of different temperature location measurements on estimated U-values.
- investigate and test different techniques to determine whole floor system U-values from many point measurements and to compare to modelled floor U-values.
- understand the extent of reduced heat-flow through a joist to account for this in whole floor U-value estimates and in comparison with models.
- understand the impact of all of the above on in-situ floor U-value data collection techniques and to lead to refinement and further development of floor U-value measuring methods.
- to understand the influence of floor void ventilation on observed U_p-values by closing the airbricks in a controlled experiment.

This study enabled the characterisation of the Salford EH floor U-value with sealed and unsealed airbricks as well as the testing and refinement of in-situ measuring techniques and analysis methods in a controlled environment without the problems associated with field measurements in occupied houses, such as changing environmental conditions and occupant space heating patterns, as noted in Section 4.2.2. A survey revealed that uninsulated central heating pipes ran across the entire floor void perimeter. Hence the internal chamber was heated electrically to enable investigation of the floor heat-flow perimeter effect. It was also agreed to minimise other studies taking place at the same time in the Salford EH, including undertaking of blower door tests, to avoid affecting data collection and analysis.

4.3.1. Description and research design

The Salford EH is separated on one side from an adjoining smaller house in the environmental chamber by a solid brick party wall. This neighbouring property was heated continuously to 18ºC throughout this study. The suspended timber ground floor was just 28.46m^2, with timber floorboards in the living area and tiled floor finish in the kitchen on top of plywood and floorboards. The externally measured exposed perimeter was 16.34m with seven airbricks, totalling 0.00077m^2/m ventilation area per metre of exposed perimeter. While the reconstructed construction elements and imposed climatic conditions were a simulation of the actual environment, there were several variables which were not replicated from an actual house:

- the construction of the environmental chamber in which the Energy House is located is built to newer construction standards than pre-1919 houses: the chamber stands on a 280mm thick concrete slab, which in turn stands on top of an insulated ground floor slab, collectively referred to as the concrete substructure; see *Figure 17*.
- floor void ventilation occurred in between both houses with no airbricks on the back facade (see *Figure 18*.); the above mentioned void ventilation area excluded this opening area.
- solar gain cannot be replicated in the EH, while wind-speed was excluded but the house was subject to air-circulation from the external chamber air conditioning system.
- there was only a 50-70mm gap under the 190 mm joists and the concrete oversite slab which was likely to have reduced free airflow in the void. Note that joists run from gable wall to party wall as indicated on *Figure 18*.
- the floor finish was tongued and grooved floorboards apart from ten floorboards, which had gaps between them; as shown on *Figure 18*. This hybrid is atypical of floors of this kind.
- the Salford EH was an unoccupied and controlled environment at all times which was held near-constant for most of the year at winter temperatures in the external chamber (~5-6ºC) and internal temperatures of 18-20ºC in the living spaces, as was the case during this study. This means that the thermal behaviour of the concrete substructure was in equilibrium, while in an actual house, the ground's thermal mass below the floor is unlikely to be in equilibrium throughout the day and interseasonally. It is unknown what the effect of this was on the study.

Despite these limitations, the environmental chamber allowed for near steady-state conditions, reducing measurement time and facilitating repeated measurement of the physical variables, reducing the variability of heat-flow through the floor - as discussed in Section 4.3.4. The Salford EH enabled the investigation of the spread of heat-flow across a construction element under conditions which are not otherwise possible in occupied dwellings, such as:

- high-resolution monitoring (i.e. at many points on the floor; for definition, see Chapter 2.10.;
- heating the neighbouring house to a constant 18ºC;
- the ability to electrically space heat to avoid heat-flow from uninsulated radiator pipes in the floor void affecting heat-flow measurements;
- control of (and close replication of) internal room conditions, avoiding unpredictable heating occupancy patterns and behaviours;
- control of the external environment at 5ºC and without wind effects and solar gain, creating a large temperature differential between the internal and external environment and reducing the number of variables that usually occur in field measurements such as changing wind direction and wind-speeds, solar gain etc, which are likely to affect measurements.

Figure 17. Shows the Salford EH on its concrete plinth in its external environmental chamber. Image credit Salford (2013).

Note that the total floor void ventilation area was about 50% of the current UK Building Regulations minimum requirement of 0.0015 m^2/m (NBS, 2013) for timber floor ventilation, considered sufficient to avoid high relative humidity in floor voids which could lead to timber rot. The pilot case study house also had ventilation openings significantly below the current recommendations *(see Table 21., page 183)*. This might reflect that dwellings built around this time might have lower than current ventilation requirements, however a larger scale survey of the UK housing stock would be required to confirm this.

4.3.2. Instrumentation, fixings and location of instruments on the floor

Measured variables included external environmental chamber air temperature (T_{ea}, ºC), heat-flux (q, mV) and internal surface temperatures (T_{Si}, ºC) in 15 locations on the bare floorboards of the uninsulated floor of the living room, as shown in *Figure 18*. For the Salford EH, Hukseflux HFP01 heat-flux sensors were used with an instrument accuracy of ± 5%; and 110PV surface temperature thermistors, with an accuracy of ±0.2°C, alongside type K thermocouples (±1.0ºC). A mix of data loggers were used: two Eltek Squirrel-851L, one Campbell CR-10X, 1000 and 3000. To ensure good surface contact, all heat-flux and surface temperature sensors were surface-fixed with a thin layer of servisol heat-sink compound (thermal conductivity = 0.9 $Wm^{-1}K^{-1}$, (Farnell, 2014)) and were secured with masking tape in the middle of a floorboard to measure floor board surface temperatures, directly adjacent to the heat-flux sensors (unlike on top of the heat-flux sensors in the 2012 pilot case-study house). Areas of floor were sought which broadly represented the conditions and structure of the floor, with minimal influence from local heat gains and other influences (CEN, 1996, BSI, 2014); floorboard gaps and joist locations were avoided, apart from location 11 in the Salford EH study, which was purposively measured on a joist location. An infrared camera was used in both monitoring studies to aid sensor placement as recommended by BSI (2014), ASTM (2007a, 2007b) and McIntyre (1985).

Masking tape of similar colour and emissivity to the floorboards was used to create similar radiant and reflective surfaces, though the middle of the sensor, i.e. the active sensing part, was kept free from any tape or instruments in the Salford EH (and was hence of different colour and emissivity). Contrary to this, in the pilot study the surface temperature sensors were located and taped onto the sensing part after Baker (2011b). In both studies, sensor edges were smoothed with the same masking tape to minimise turbulent flow over the sensors as advised by Bales (1985) and as described in Chapter 3.3.

To investigate use of different temperatures on U-value estimation, air temperatures within the Salford EH living room were measured at different heights (100mm, 600mm, 1100mm, 1700mm)[5] in the middle of the room, alongside external chamber temperatures (T_{ea}, °C), with HOBO-U12 sensors (±0.35°C). A temperature difference between internal surface temperatures and external chamber air of minimum 8°C was maintained during the entire monitoring period. All measurements were taken at 1 minute sequential intervals and analysed at hourly intervals as discussed in Section 4.3.4 and as also discussed in Chapter 3.3.

In the Salford EH, floor measurement locations were purposively sought in the perimeter zone, taken to be within 1000mm from an external wall (sensor locations 10, 11, 12, 13 - *Figure 18.*). Areas near airbrick locations (1, 9, 14) in the void below were also observed. Locations 2, 3, 4, 5, 6, 7, 8, 15 were outside the perimeter zone and away from airbricks and allowed the investigation of heat-flow in these different areas. Location 11 was measured on a joist - see *Figure 18*. No clear sensor location grid could be obtained due to floor board unevenness and due to safe and trip-free access to the EH which had to be maintained at all times and taking into account door opening swings. *Figure 19*. gives an overview of the instruments on the floor surface in the living room area.

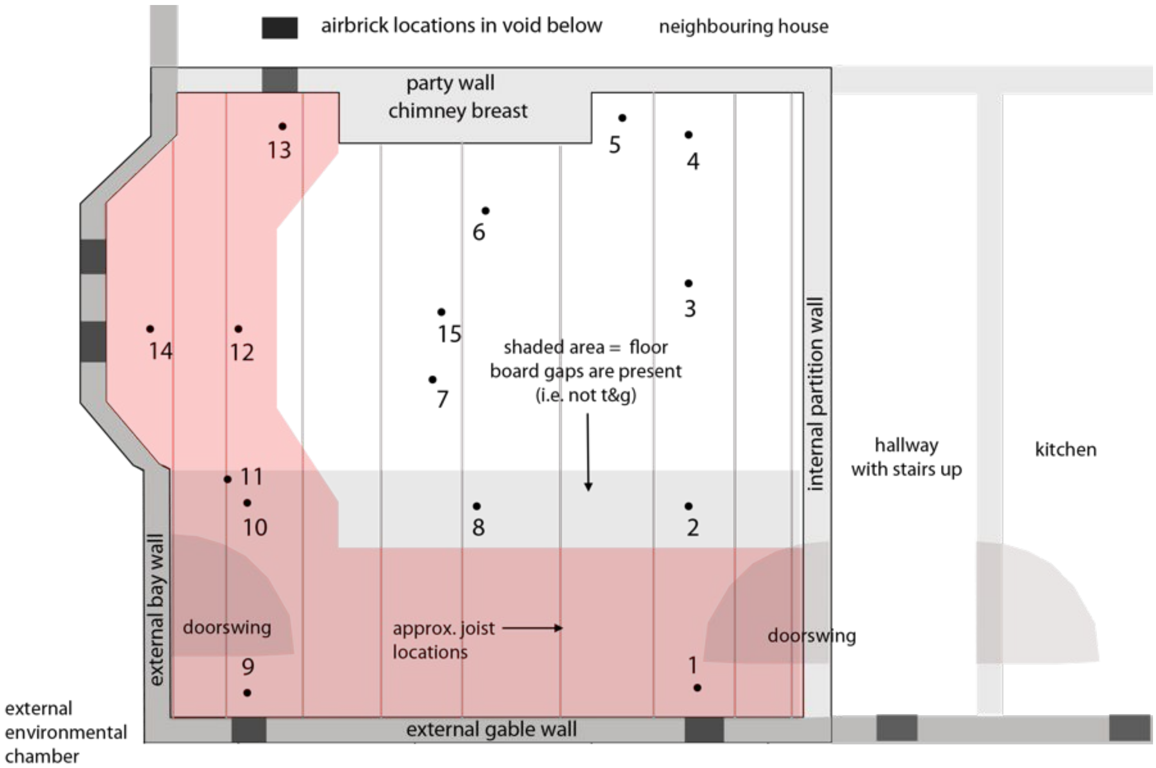

Figure 18. Salford EH living room plan and in-situ point measurement locations; note that sensor location 11 was on a joist. The red zone indicates a 1000mm perimeter zone in the living room.

[5] In accordance with thermal comfort standard BS-7726 (BSI, 2002), though thermal comfort findings are not reported here for the Salford EH.

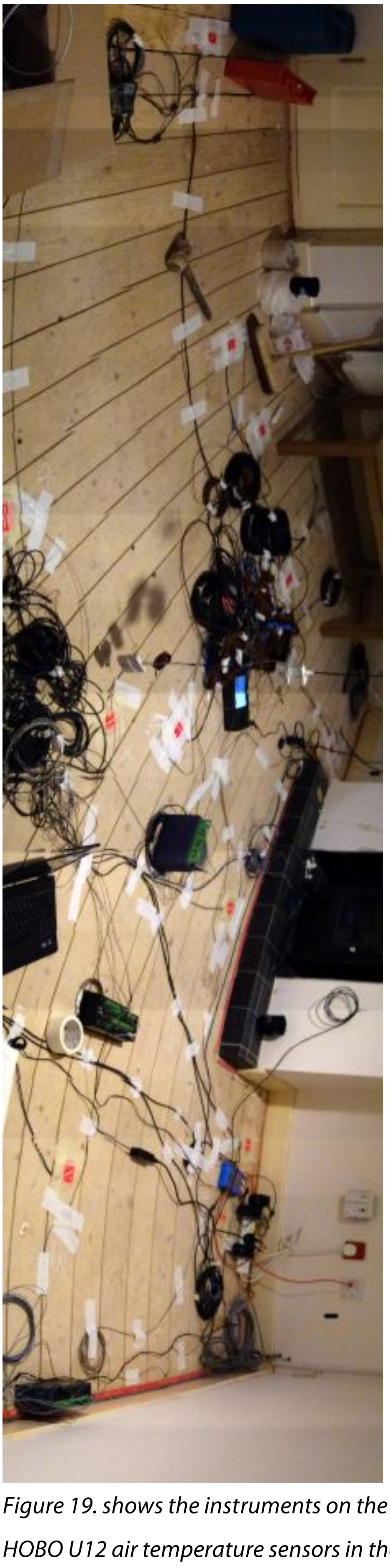

Figure 19. shows the instruments on the floor surface in the living room area and the suspended HOBO U12 air temperature sensors in the middle of the room.

4.3.3. Side by side 'calibration' checks in the UCL thermal lab

A 'side by side' calibration check of the UCL heat-flux sensors was undertaken similarly to the method deployed by Doran (2008), alongside side by side calibration of the HOBO-U12 sensors and two available thermistors. Equipment that had been borrowed had to be returned before being able to perform the same checks. The purpose of the side by side calibration was to establish if there was any drift by any of the sensors when measuring the same quantity in a thermal lab under steady-state conditions. A side by side calibration is best supported by one heat-flux sensor being re-calibrated in a hot box, against which all others sensors in the side by side experiment can then be compared, as undertaken by Doran (2008), however due to limited resources this could not be achieved for this study. Sensors could also only be tested at one temperature setting, due to another experiment taking place at the same time in the UCL thermal chamber; the chamber temperatures were higher than those at the Salford EH: 20-23ºC on the warm side and 12-13ºC on the cold side. Temperature sensors could be tested at the two chamber conditions by swapping them half way through from one chamber to another, but could not be checked at the lower Salford EH temperatures (5-6ºC).

The UCL thermal lab was not designed with the purpose for calibration;[6] despite this, good agreement was indicated between all sensors and their own accuracies, suggesting that a bias was unlikely. U-value results indicated that the heat-flux sensors were within ±5% of the mean of the group of sensors and also between each other. Furthermore, no drift was expected as most of the heat-flux sensors were <2 years old, below the time-period where re-calibration is recommended (BSI, 2014).

No individual instrument or data adjustments were undertaken as exact measuring conditions could not be repeated in the chamber and accuracies were all within those stated by the manufacturer; assumed instrument errors were included in the final error propagation - as described in Chapter 3.3 and Section 4.3.4.

[6] For example the separating wall between the internal and external environmental chamber is made up out of different insulation materials in small sections with timber joists inserted, requiring the careful placement of sensors to ensure that the measured heat-flow is comparable between sensors. Additionally, hot and cold chamber temperatures are measured close to the fan outlet and hence are unreliable for calibration with temperature sensors; this may also create uncertainty in the calibration itself due to different air-flow patterns over sensors.

4.3.4. Error propagation and data analysis procedures

As discussed in Chapter 3.3.4., in-situ measuring is affected by instrument and measuring condition errors; additionally the natural variability of U-values in changing environmental conditions affects the U-value estimation. For the Salford EH, the natural variability of U was derived from one standard deviation (*sd*) between hourly obtained U-values as in *Equation 49.* For the 2012 pilot study, daily data was used for the estimation of U-values and their natural variability component - as explained in Chapter 3.3.4.3.

The natural variability component of U is estimated in the field as ±10% by BSI (2014) and as expected this was significantly reduced for the Salford EH: ±1% to ±4% with sealed airbricks and ±2% to ±5% with open airbricks depending on observed point location (and after research influence outlier removal - see Section 4.3.5.). Overall this constituted a small component of the total measurement uncertainty, resulting from undertaking measurements in a near steady-state chamber. However, for the pilot study, the natural variability of U was estimated between ±13% to ±19%,[7] reflecting the changing environmental conditions in the field.

A summary of the errors allowed for in the final error estimate is provided in *Table 9.* in Chapter 3.3.4.3. As the conditions in the Salford EH were near-steady state, the natural variability constituted a small component of the total uncertainty, which was ±9 to ±11% depending on point location and whether airbricks were open or closed.

During the monitoring period, there was some researcher influence when data was collected or activities took place in the external chamber; outliers were removed by Chauvenet's Criterion as described in Section 4.3.5. Results are presented rounded to two decimal places and in accordance with *Equation 47. or Equation 48.* (see Chapter 3.3.4.3), depending on use of surface or air temperatures respectively.[8] Total measurement uncertainty was derived as per *Equation 49.* or *Equation 50.* in comparative studies - see Chapter 3.3.4.3.
The thermal resistance of the heat-flux sensor itself (~ 6.25 x 10^{-3} m^2K/W, (Hukseflux)) was accounted for by adjusting collected data; while sensor placement errors were minimised by careful sensor placement with use of an infra-red camera as described in Chapter 3 and Section 4.3.2.

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7 Depending on location on the floor and height of the air temperature measurement used.

8 Where surface temperatures were used to estimate the point U-values, estimates require adjusting with assumed surface resistances to account for airflow and radiative effects at the surface as also undertaken by Baker (2011b), Rye (2010) and Doran (2008) for solid wall research - see Chapter 3.3.4.

4.3.5. Data checks, outliers and Chauvenet's Criterion

Outliers caused by researchers' influence during airbrick-open data collection were removed using Chauvenet's Criterion. Chauvenet's Criterion is a statistical and objective test which identifies outliers in normally distributed data. The test determines a 'distribution band' to identify outliers, assuming a normal distribution with mean and standard deviation corresponding to those of the data (Bayless., n.d., Taylor, 1997). The normality assumption is used to calculate the probability that each data point would be observed if it did belong to the data. This probability is then multiplied for the number of observations in the data; if for any observation point the result of this calculation is ≤0.5, the data point is considered as an outlier that is highly unlikely to have been produced by the same process that produced the rest of the data (Lin, 2007, Bayless., n.d., Taylor, 1997).

Removal of outliers should always be treated with caution (so as to not bias the data and/or to discard evidence of significance) and is ideally only removed if it is known why this outlier occurred and can be identified as an error (Taylor, 1997), as was done here. Chauvenet's Criterion has been criticised by for example Ross (2003), arguing that the ≤0.5 requirement described above is arbitrary; however applying Chauvenet's Criterion is widely accepted (Taylor, 1997, Bayless., n.d.); and it might be less arbitrary than manual outlier removal.

Manual outlier removal based on identified researcher influence gave similar U-values and standard deviations as outlier removal with Chauvenet's Criterion. As such, in this PhD research, Chauvenet's Criterion was only used for removal of outliers which were known to be errors caused by researcher's influence as was the case for the Salford EH airbricks-open data. No significant research interference took place during the airbrick-closed monitoring period, thus no Chauvenet's Criterion adjustments were made for that data set.

Chauvenet's Criterion reduced the 120 hour airbrick-open data by between four to eleven hours (max. 9% removal) depending on sensor location - see *Table 16*. Outlier removal did not significantly change mean U-values; it was however undertaken as there were some clear outliers which affected the estimation of the natural variability of U significantly and hence the final uncertainty estimates - as can be noted from *Table 16*. Using Chauvenet's Criterion lead to slightly higher (0-3%) estimated U-values compared to U-values estimated from the data including the outliers (see *Table 16.*).

In all floor locations, peaks were observed in the morning of May 13th when data was collected due to data logger memory limitations. A more significant peak, with its effect lasting for several hours, was on May 14th and was explained by the researchers at the Salford EH gaining increased access to the internal and external chamber to prepare for a new research project the next day. This researcher influence was most evident in locations 1, 2 and 9 and are illustrated by surface temperature and heat-flux data (q, W/m^2) plotted in *Figure 20.* for location 9. Both locations 1 and 9 were nearest to the airbricks in the gable wall and also nearest to the door swings to enter the chamber and the kitchen - see *Figure 18*. Increased floor surface temperatures were observed in these locations due to temporarily obstructed airbricks along the external gable wall (and hence a warmer void), leading to temporarily reduced heat flow q - illustrated for location 9 by *Figure 20. Figure 21*. illustrates the same data in location 9 after removing the anomalies with Chauvenet's Criterion: a total of 4 outlier hours on May 14th were removed this way. Without removal of the outliers, the standard deviations were significantly larger especially in locations 1 and location 9 - see *Table 16.*

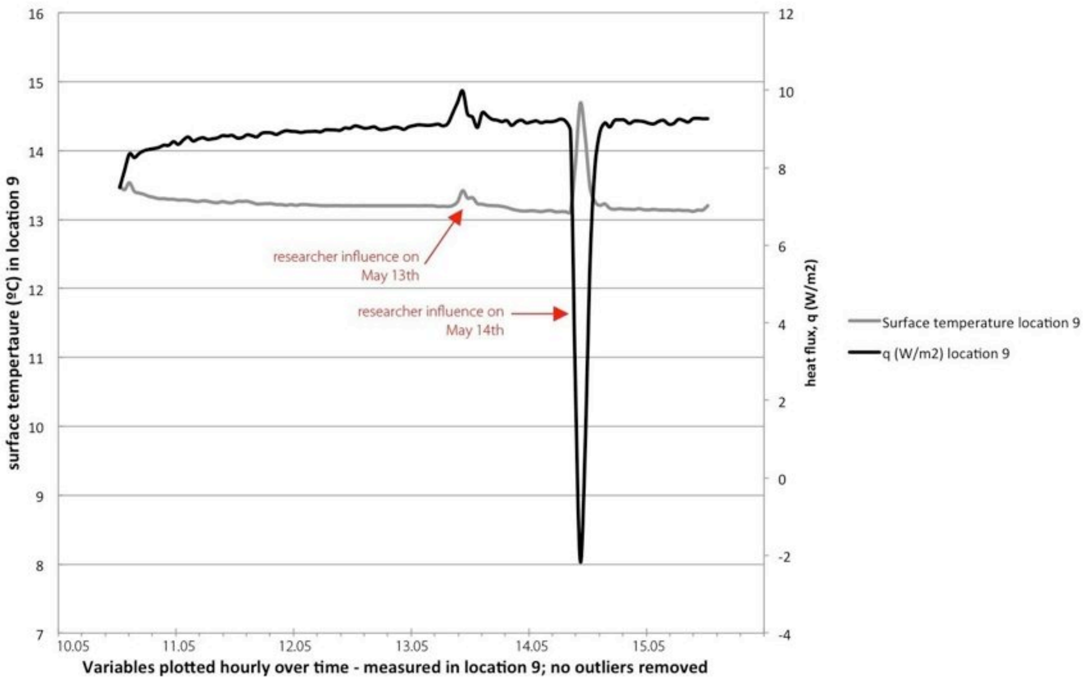

Figure 20. Hourly surface temperature (ºC, grey line) and heat-flux data (q, W/m^2, black line) in location 9 over time (5 days). Peaks show researcher influence as described in text.

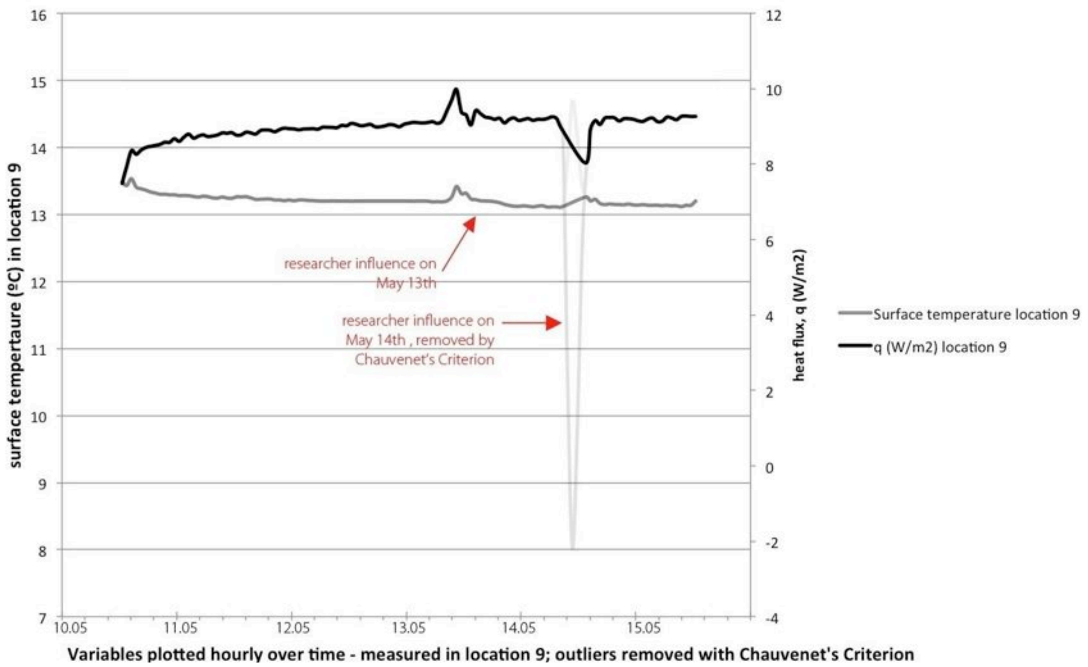

Figure 21. Hourly surface temperature (ºC, dark grey line) and heat-flux data (q, W/m^2, black line) in location 9 over time, with data treated with Chauvenet's Criterion (removed data visible in light grey line).

Estimating daily U-values instead of hourly had a similar smoothing effect as outlier removal, including reduction of standard deviations, as illustrated for location 1 and 9 in *Table 17*. However given that only 3 to 5 days of data were available for the monitoring period with airbricks closed or open respectively, the hourly Chauvenet treated data was considered more suitable for use, while acknowledging associated issues with outlier removal as described above.

OPEN AIRBRICK	mean U-value (hr)	mean U-value (hr), outliers removed	% diff U	sd, (hr)	Sd, (hr), outliers removed	% diff sd	hrs removed	% sd before outlier removal	% sd after outlier removal
	($Wm^{-2}K^{-1}$)			($Wm^{-2}K^{-1}$)					
HF1	0.72	**0.73**	-1.87	0.08	**0.03**	62	6	*11*	*4*
HF2	0.72	**0.72**	-0.46	0.05	**0.04**	18	10	*6*	*5*
HF3	0.66	**0.66**	-0.60	0.03	**0.02**	22	11	*4*	*3*
HF4	0.61	**0.61**	-0.38	0.02	**0.02**	15	9	*4*	*3*
HF5	0.56	**0.56**	-0.12	0.01	**0.01**	24	11	*3*	*2*
HF6	0.67	**0.67**	-0.10	0.02	**0.02**	18	9	*3*	*2*
HF7	0.77	**0.77**	-0.20	0.02	**0.02**	15	9	*3*	*3*
HF8	0.81	**0.81**	-0.04	0.03	**0.02**	17	6	*3*	*3*
HF9	0.90	**0.92**	-2.74	0.15	**0.03**	78	4	*16*	*4*
HF10	1.16	**1.16**	-0.33	0.04	**0.02**	32	10	*3*	*2*
HF12	1.02	**1.03**	-0.60	0.05	**0.03**	24	8	*4*	*3*
HF13	1.08	**1.09**	-0.27	0.05	**0.03**	28	8	*4*	*3*
HF14	1.17	**1.18**	-0.41	0.04	**0.03**	29	6	*4*	*3*
HF15	0.69	**0.70**	-0.25	0.02	**0.02**	21	10	*3*	*2*
HF11 (joist)	0.92	**0.92**	-0.51	0.04	**0.02**	34	11	*5*	*3*

Table 16. Highlights the similarities and differences between U-values estimated from Chauvenet's Criterion treated and original data without outliers removed, alongside their standard deviations and total hours removed per observed location. Note especially the decreased standard deviations (sd, final column) as a % of the total U-value after outliers were removed using Chauvenet's Criterion.

Considering that the Salford EH is kept at near steady-state, small standard deviations were expected and were <5% for the original data for all locations apart from locations 1, 2 and 9, correlating with the local researcher influence affecting these locations most (see final two columns in *Table 16.*). In general, the standard deviations were relatively small compared to the other assumed measurement errors, as listed in Chapter 3.3.4.3., *Table 9.*

Hence the standard deviation as the representation of the natural variability of U over the monitoring period had a small impact on the overall combined estimated uncertainty. After the outlier removal data, the *sd* is for all locations small (< 5%, see *Table 16*) - as would be expected from measurements in a near steady-state environment and as described in Section 4.3.4. and Section 3.3.4.

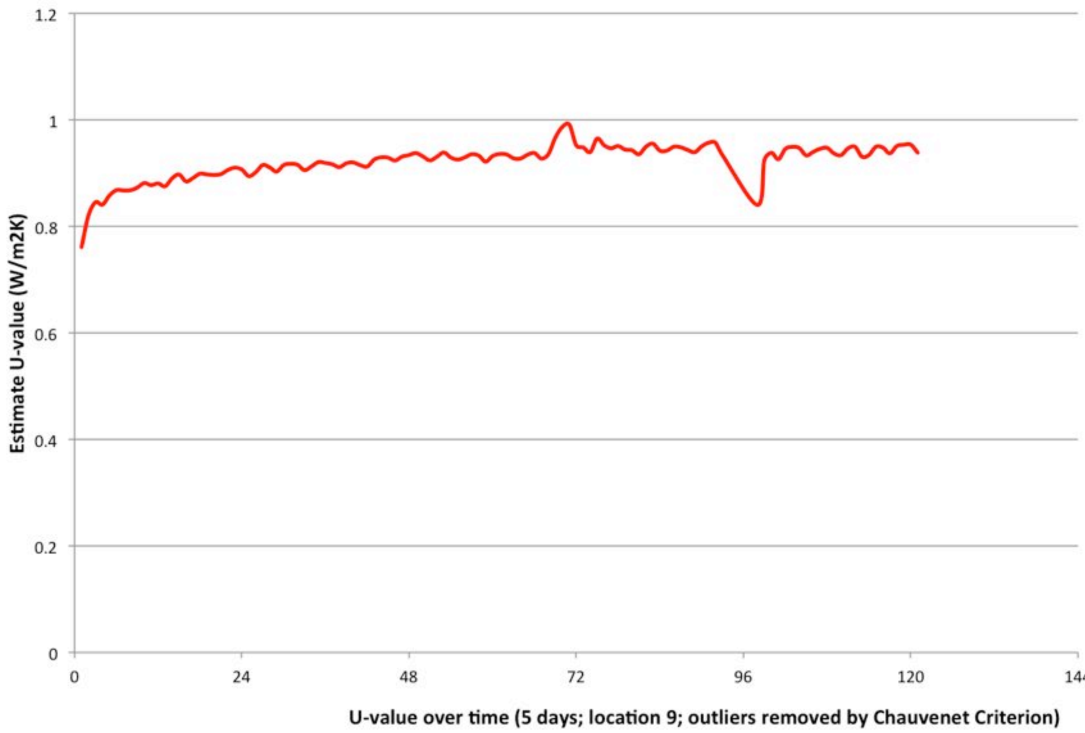

Figure 22. Estimated hourly U-value in location 9 over time, data treated with Chauvenet's Criterion; estimated with Equation 47.

As can be seen from *Figure 22*., a slight upward trend of the hourly estimated U-values was observed in the first few days; this was similarly recorded for all locations on the floor and might be explained by the closing of the airbricks directly prior to the monitoring of the heat-flow with open airbricks. The closing of airbricks was likely to lead to the void warming up and storing more heat in the concrete substructure, which in turn - once airbrick covers were removed - lead to the thermal mass of the sub-floor void releasing this stored heat to a now colder void after colder external chamber temperatures entered the void. From *Figure 22.* it was suggested that it took about 48 hours for the thermal mass to settle and reach steady-state after unsealing the airbricks. As such, including the first few days of data as was done here might lead to a slight downwards bias for the 5 day estimated U-values; though in some locations this might be partially offset by slightly higher estimated U-values after applying Chauvenet's Criterion to remove the outliers from researcher influence as described above. From *Table 17.* it can be noted that for the first 3 days data and full 5 day data, standard deviations are larger than the small differences between the estimated mean U-values, suggesting that inclusion of this data did not significantly bias U-value estimation (i.e. within their natural variability margin). Towards the 5th day of monitoring, U-values settled and the ISO ±5% test criteria (see Chapter 3.3.1) were met prior to stopping the monitoring campaign.

Doing so was useful to ensure data collection was not terminated too early, ensuring sufficient data were collected where U-values settled to a stable value.[9]

Finally, all mean estimated U-values were very similar when obtained from 1 minute, 15 minute, hourly and daily averaged data, apart from the hourly U-values obtained from the first three days which avoided the research influence in day 4 and day 5 and which appeared slightly biased low due to the issues described above. This is illustrated for location 1 and 9 in *Table 17.* As expected, estimating U-values from daily data smoothes the data so that the effect of outliers was absorbed within the daily mean, leading to small standard deviations - similar to the standard deviations obtained after applying Chauvenet's Criterion to hourly data (*Table 17., Chauvenet Criterion comparison in italics*). This indicated that for the Salford EH, the hourly mean was a good approximation to the true mean.

	U mean, daily data (5 days)	**U mean, hourly data**	**U mean, first 3 days**	**U mean, 15 minutes data**	**U mean, 1 minute data**
			$Wm^{-2}K^{-1}$		
Location 1, original data	0.72 ±0.03	0.72 ±0.08	0.71 ±0.03	0.72 ±0.09	0.72 ±0.10
Location 1, outliers removed Chauvenet Criterion	*no outliers*	*0.73 ±0.04*	*no outliers*	*0.73 ±0.04*	*0.73 ±0.05*
Location 1, original data	*0.90 ±0.04*	0.90 ±0.15	0.91 ±0.04	0.90 ±0.15	0.90 ±0.17
Location 9, outliers removed Chauvenet Criterion	*no outliers*	*0.92 ±0.03*	*no outliers*	*0.92 ±0.05*	*0.92 ±0.08*

Table 17. Estimated U-values for location 1 and 9, depending on resolution of data (daily, hourly, 3 days, 15 minutes and 1 minute data) used for analysis; including the use of Chauvenet's Criterion, highlighted in italics.

[9] If this had been done during the pilot study, there would have been no need to measure for as long as 23 days, as 'valid' U-values were already obtained after just 3 days, the ISO-9869 minimum valid timescale.

4.4. Analysis, results and discussion

All U-values presented for the Salford EH are mean U-values from hourly analysed data, with adjustment for the heat-flux sensor itself and estimated from measured internal surface temperature to external environment temperatures, adjusted with an internal surface thermal resistance of R_{Si}= 0.17 m^2KW^{-1}, unless stated otherwise. As described in Section 4.3.1 and 4.3.2, 15 locations on the living room floor were observed, as marked on *Figure 18*.

Point U-value estimates of these locations ranged between 0.56 ±0.05 $Wm^{-2}K^{-1}$ in location 5, furthest away from the external walls and 1.18 ±0.11 $Wm^{-2}K^{-1}$ in location 14, in the bay window area. Location 11 was measured on a joist and had an estimated U-value of 0.92 ±0.09 $Wm^{-2}K^{-1}$; 21% relative change compared to the adjacent floorboard U-value in location 10 and outside the estimated margins of error.

4.4.1. Large spread of observed U-values and perimeter effects

U-values in different locations on the floor varied widely, ranging from 0.56 ±0.05 $Wm^{-2}K^{-1}$ to 1.18 ±0.11 $Wm^{-2}K^{-1}$ - see also *Table 22.* in Section 4.4.4. Such variation is expected because as the distance from the floor to the external environment changes, the total thermal path also varies and ventilation rates also vary at different distances from the airbricks and airflow paths. As the distance from the exterior walls increases, the point U-value is expected to decrease, which has been noted for solid ground floor heat-flow by Delsante (1989), Trethowen (n.d.) and Thomas (1999). While conduction and convection heat-flow from a location on the floor to the external environment (e.g. through the void air layer and the ground) is inversely proportional to the distance between the warm and cold environment (i.e. heat-flow reduces as this distance increases), in a real suspended ground floor it is unlikely that such clear relationship would hold due to the different influencing factors and the complex three-dimensional nature of heat flow and ventilation. This is because, as discussed in Chapter 2, there are other heat-flow mechanisms at play in suspended ground floors: radiation; ventilation from other sources; conduction through foundation walls and geometric influences. However, given the complexity of the heat-flow and airflow paths, the proportional influences of each of the contributing variables remain uncharacterised. For example it is unknown what a typical airflow path is or the effect of the airbricks, which are likely dependent on void obstructions such as sleeper walls and joist locations. Additionally ventilation rates are likely to vary considerably in the floor void due to changing wind-speeds and wind directions in the field (Hartless, 1994).

Because airbricks are located at the edges of a building, the main effect of airflow on the heat-flow rate is generally expected in the floor perimeter area; however it was not possible to isolate the effect of the airbricks in the perimeter walls. Generally increased void ventilation leads to an increased rate of heat-flow, because:

- the void air layer is not a still air layer, hence creating mass-transfer heat-flow;
- in winter, colder external air displaces warmer void air, creating a greater ΔT between internal spaces and the void, increasing the rate of conductive heat-flow to the void. A large temperature variation across the floor can be inferred from the below infrared image *Figure 23.*;
- surface thermal resistances in the void are likely to be lowered, reducing resistance to heat-flow - as described by Harris (1993).

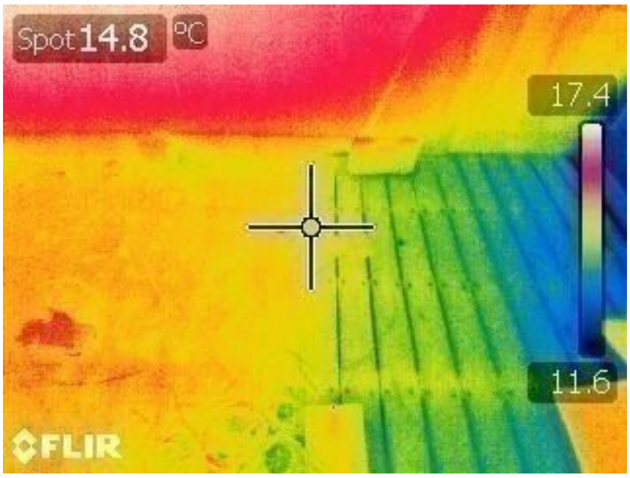

Figure 23. Infrared image of a section of the Salford Energy House floor surface, illustrating the spread of surface temperatures across the floor with airbricks open. In-situ measured surface, temperatures ranged between 16°C near the back of the room (illustrated here in yellow), compared to just 13°C near airbrick s(illustrated here in blue).

Each estimated point U-value was investigated as a function of its nearest distance to an exposed wall - see *Figure 24. Figure 24.* supports a relationship between heat-flow and distance to nearest external walls; and this was in support of hypothesis H2 (*"There will be increased perimeter U_p-values observed compared to locations further away from the external wall (i.e. the non-perimeter zone)"*). To test this hypothesis, simplified categorisation of estimated U_p-values in perimeter and non-perimeter zones was undertaken: Delsante (1989) described a narrow strip of a 1000mm perimeter zone for solid ground floors where most of the heat loss occurred, though for larger floor areas. Thomas (1999) describes a 1500mm perimeter zone also for a large solid ground floor.

For the Salford EH, a 1000mm perimeter zone categorisation would include six measurement locations in the perimeter zone and eight in the non-perimeter zone; while a 1500mm perimeter zone would reverse this. Given the small floor plate of the Salford EH and other floors studied in this PhD research, the categorisation of the 1000mm perimeter zone was used as it allowed sufficient points to be included in the perimeter zone, while maintaining the definition of perimeter as not the majority of the floor area. However, it should be highlighted that this perimeter categorisation and grouping is for the purpose of hypotheses testing and to allow graphical representation of U_p-values within 1000mm from an exposed wall.

Hypotheses can be tested by undertaking statistical tests of the data. The Wilcoxon or Mann-Whitney U test is a hypothesis or significance test (Spiegel, 1999) and was used here instead of the more common *t*-test. Unlike the *t*-test, the Wilcoxon test does not assume normal distribution nor equal standard deviations between the two comparison groups and is therefore often preferred (Dytham, 2011). Additionally, the Wilcoxon test is less likely to return a result of significance when there is no real difference (Dytham, 2011); statistical hypothesis testing excludes error margins.

To test hypothesis H2, the U-values within a 1000mm perimeter zone (i.e. locations 1, 9, 10 and 12 to 14; *Figure 24.*, in red) were compared with the non-perimeter zone of the floor (points in black) by an unpaired Mann-Whitney U (Wilcoxcon rank sum) test, suggesting that the observed U-values in the perimeter and non-perimeter floor zone differed significantly (Mann–Whitney $W = 46$, $n2 = 6$; $n2 = 8$, $P < 0.05$ (0.002664), unpaired). The probability that there was a zero difference in heat-flow between the perimeter zone and the non-perimeter zone of the floor was negligible (0.002664, or about three in 1000). The estimated mean U-value of the 6 perimeter located points was 1.02 ±0.10 $Wm^{-2}K^{-1}$ which is about a third greater than the estimated mean U-value of the non-perimeter zone (0.69 ±0.07 $Wm^{-2}K^{-1}$). Increased U_p-values nearest the external environment also follows physical principles as described prior; though it should be noted that there is no clearly defined extent of the perimeter effect as there is no abrupt change after 1000mm, but a gradual reduction in U_p-values the further away from the external environment - see *Figures 24 to 29.*

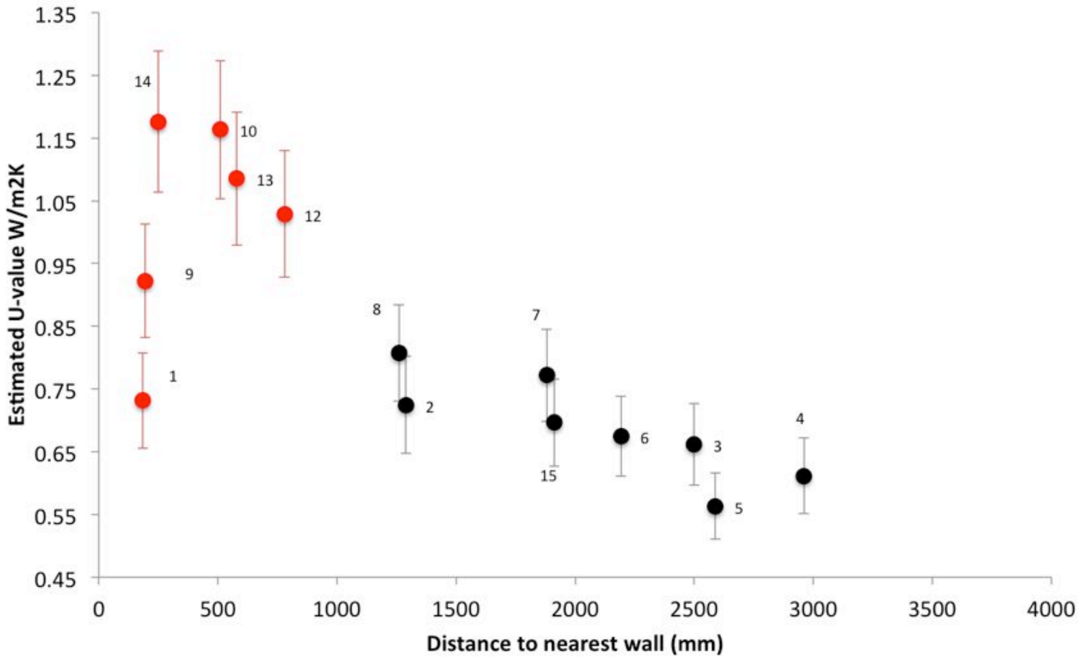

Figure 24. In-situ estimated Salford EH suspended floor U-values as a function of nearest distance to exposed wall measured from the nearest internal surface of the external wall to the middle of the heat-flux sensor; red data points are within 1000mm of the exposed perimeter; black data points are located in the non-perimeter zone.

After the monitoring period, builder's debris in the void blocking the airbrick nearest to location 14, was discovered. This is likely to have affected perimeter heat-flow in location 14 and other nearby locations, possibly resulting in reduced heat-flow than if the airbrick had been clear. It can also be noted from *Figure 24.*, that the estimated U_p-values in the perimeter zone of the bay-wall (locations 10, 12, 13, 14) were within each other's margins of error, but were outside the margins of error of the non-perimeter zone U_p-values, confirming that the bay-wall effect especially was large and significant. This is also confirmed by *Figure 26.* which plots point U-values as a function of bay-wall distances and highlights that in general there was increased heat-flow in locations nearest to the external bay-wall (10, 12 to 14) compared to perimeter locations near the gable-wall (locations 1, 9). This observation might be explained by the bay wall's two airbricks and its large exposed perimeter. Furthermore, the 190mm deep joists ran from gable to party wall (see *Figure 18.)* and allowed only about 50-70mm clearance for free airflow underneath, partially obstructing air-flow from the bay-wall floor void area into the rest of the floor void - see *Figure 25.* This might lead to an isolated area of low void temperatures in the bay-wall floor void and hence increased heat-flow in this bay perimeter area, emphasising increased U_p-values in this area. These increased U_p-values in the bay wall perimeter area emphasise the observed low heat-flow away from the bay-wall, i.e. in the gable perimeter locations 1 and 9.

Figure 25. a and b. show the limited space under the deep joists and location of the airbricks within the deep joist zone. This is likely to have channelled airflow between joists, with joists acting as obstructions to flow of air between different floor areas.

Comparing *Figure 26.* with *Figure 28.* might further confirm the above theory: there appears to be a stronger relationship between U_p-values and distance to the bay-wall (*Figure 26.*) than distance to gable wall (*Figure 28.*). The gable wall airbricks below locations 1 and 9 allow a clear airflow path between joists, dispersing cold air between the joists, unlike in the bay-wall floor void. However, as the observed lower U_p-values in locations 1 and 9 occur in the only two observed perimeter locations near the gable wall, further investigation and additional measurements such as void airflow would be required to determine the above theory as to why the gable wall is less influential in heat-flow determination.

Plotting point U-values as a function of the gable wall (*Figure 28.*) illustrates that in general, when disregarding the 4 point locations in the bay area (i.e. locations 10, 12, 13 and 14), the heat-flow is associated with distance from the gable wall. Points 1 and 9 are close to the gable wall and near airbricks and greater heat-flow is expected in these locations, as discussed per physical theory in Chapter 2.

The U_p-value in location 1 appears lower than expected; contrary to this, heat-flow in location 9 is likely affected by the bay-wall airbricks and the exposed wall junction. The low U_p-value observed in location 1 may not be an anomaly as it is far removed from the bay window, with several joist obstructions in the floor void below between this location and the bay window. In location 1, there appears an association between observed U_p-values and distance to the gable wall and airbrick in that location- see *Figure 27*. This is in support of the previous theory that the airflow from the airbrick in location 1 is unhindered and can migrate through to the back of the void between the two parallel joists, above which locations 1 to 4 are located. No similar association was found when plotting mean U-values in location 9, 10, 12 and 13, which were all aligned with the airbrick in the void below location 9.
This might be due to some influence of the bay-wall airbricks nearby and due to the unusual ventilation opening in location 13 to the neighbouring house, suggesting more complex influences and airflow and heat-flow paths might be at play in this floor zone.

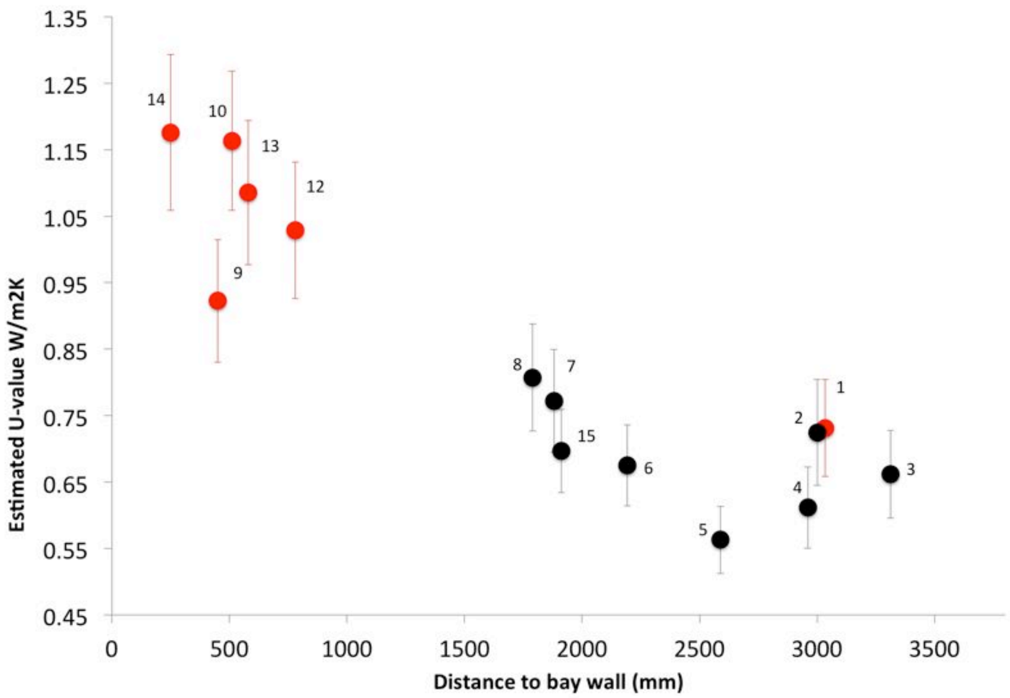

Figure 26. In-situ estimated Salford EH suspended ground floor U-values as a function of external bay wall distance; red data points are within 1000mm of the exposed perimeter; black data points are located in the non-perimeter zone.

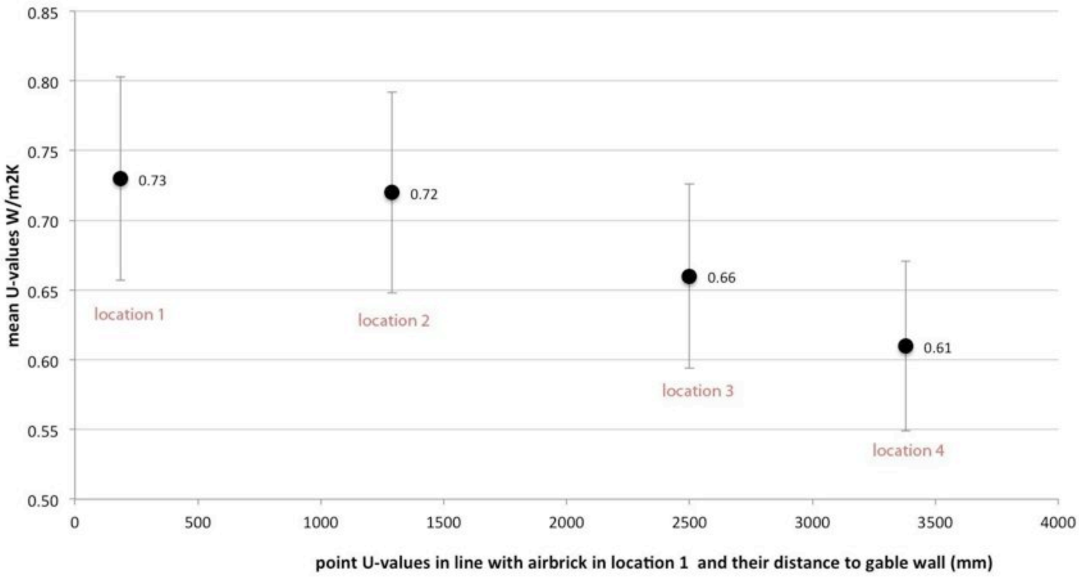

Figure 27. Plots the U-values in location 1, 2, 3 and 4, all aligned with the airbrick in location 1 in the gable wall.

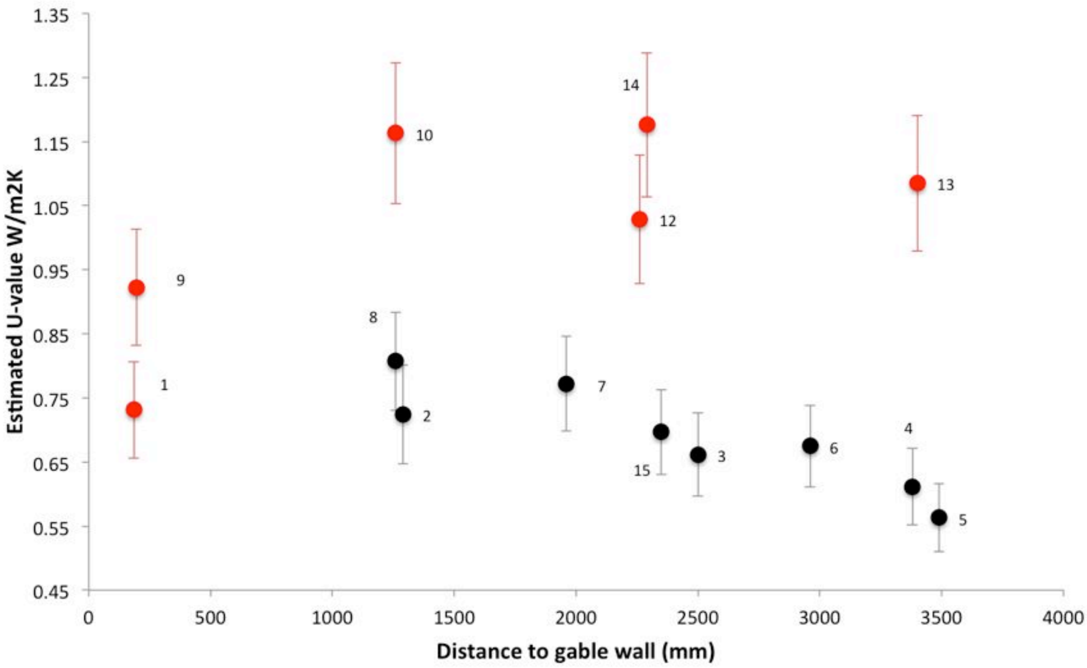

Figure 28. In-situ estimated Salford EH suspended ground floor U-values as a function of external gable wall distances; red data points are within 1000mm of the exposed perimeter; black data points are located in the non-perimeter zone.

Using combined wall distances, derived by using the electrical analogy (reducing heat-flow to a parallel resistor network, where each of the exterior walls is a heat-flow path) and plotting the distance to the external perimeter walls by regarding each distance to an external wall as a resistance to heat-flow, so that the total thermal resistance R_{tot}:

$R_{tot} \propto \dfrac{L_1 L_2}{L_1 + L_2}$ - *Equation 51.*, where *L1* is the distance to the bay-wall and *L2* is the distance to the gable wall (in mm) and where R=1/U; point U-values were plotted here to allow for direct comparison with the other graphs.

The combined wall distances appeared to be a better representation of observed floor heat-flow as a function of wall distances, visualising both the impact of distance to the bay-wall and the gable wall. In general, *Figure 29.* suggests a negative association with heat-flow and combined wall distances: i.e. the greater the combined wall distances, the lower the observed point U-values. Finally, *Figure 30.* supports hypothesis H1, indicating a large spread of heat-flow across the floor and visualises - by linearly interpolating values between points - the complex heat-flow paths and dominant effect of the bay-wall and that heat-flow is generally higher near the perimeter of the floor (H2).

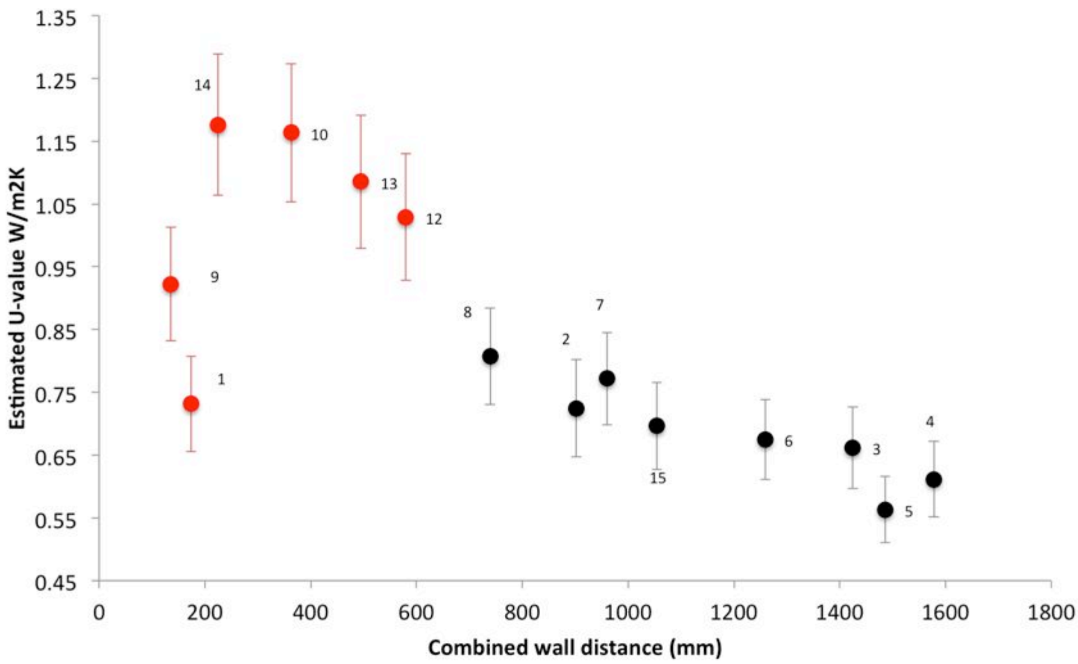

Figure 29. In-situ estimated Salford EH suspended ground floor U-values as a function of combined wall distances as per Equation 51; red data points are within 1000mm of the exposed perimeter; black data points are located in the non-perimeter zone.

In summary and in general, the Salford EH analysis provided evidence that there was reduced heat-flow with increased distance from the airbricks and external walls, in support of hypothesis H2. Furthermore, increased heat-flow was observed in the bay-wall area while the bay-wall airbricks appeared to have a limited impact on heat-flow beyond the bay area. This might be caused by the joist direction and limited clearance under the joists, restricting colder bay-wall void air movement to deeper in the floor void. This might 'skew' estimated U_p-values in the bay-wall area which may not be present in actual dwellings, depending on void construction and obstructions.

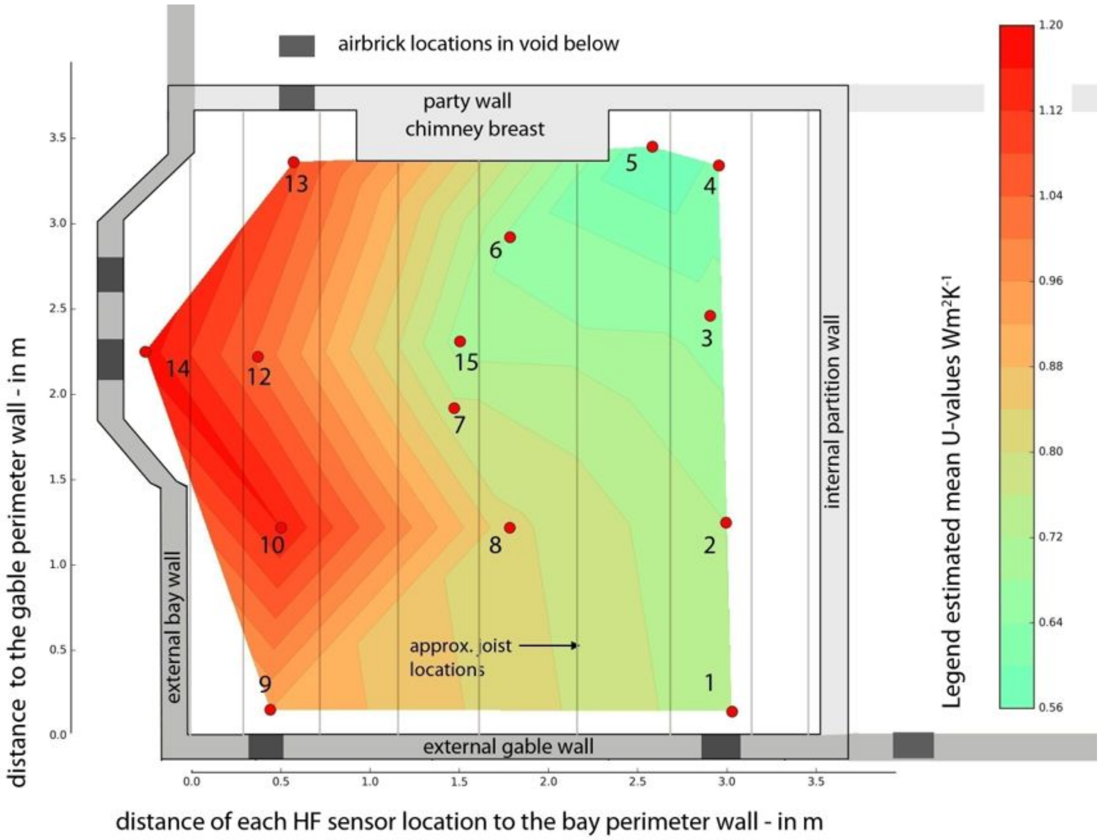

Figure 30. Individual point location U-values (marked in red) and linear interpolated U-values (in between the known point U-values) as a function of both bay (X-axis) and gable (Y-axis) wall distances. Note that Figure 30. aids visualisation of trends of floor U_p-values in the Salford EH living room but is not intended to provide a prediction of U-values between measurement points; no account is taken of structural factors, such as floor joists and only values between points are estimated (hence white zones between point locations and room boundaries).

4.4.2. Whole floor U-values: different estimation techniques

As discussed in Chapter 3.3.2., for comparison of in-situ U-values to literature and modelled U-values, a whole floor estimated in-situ U-value is needed. Yet a single in-situ point U-value, which is estimated from heat-flux through a sensor area of 30mm diameter, is unlikely to be representative of an entire element (ASTM, 2007a). This is especially the case where a high variable heat-flow across a construction element is observed, such as expected and demonstrated with the Salford EH ground floor construction. Following on from this, three whole floor U-value estimation techniques were investigated for the Salford EH, as listed and discussed in more detail below.

The Salford EH in-situ floor U-value of the living room was - in the absence of other data - assumed to be representative of the whole floor U-value of the Salford EH; the living room area was 47% of the entire Salford EH floor area (i.e. 13.33 m^2 of 28.46 m^2).

4.4.2.1. Estimated mean U-value of all 14 estimated point U-values

ISO-9869 ((BSI, 2014) states that *"sensors shall be mounted in such a way so as to ensure a result which is representative of the whole element*" and that "*it can be appropriate to install several HFMs [heat flow meters] so as to obtain a representative average*".

As discussed in Chapter 3, infrared thermography can help select representative areas, however with a large spread of heat-flow across the floors, determining which point measurement(s) across the floor are representative of the whole floor U-value is not straightforward. While averaging point locations to estimate an entire construction element's U-value is as advised by ISO-9869, using the estimated mean U-value for the whole floor U-value is only appropriate where measurements taken are representative and evenly distributed across the floor and data is normally distributed (as was the case for the Salford EH observed point U-values). The estimated mean whole floor U-value of the Salford EH was 0.83 ±0.08 $Wm^{-2}K^{-1}$; the whole floor error was estimated by averaging the individually estimated error margins.

4.4.2.2. Grouping estimated point U-values

Grouping and weighting point U-values according to their location on the floor might be more useful than simply averaging point U-values, especially because (a.) the number of measurements might be unevenly distributed across the floor surface, as might be the case in field work and (b.) because increased U_p-values are expected in perimeter versus non-perimeter zones.

For example, a group of U_p-values could be taken as representative of a floor zone with a certain area. Each group of U_p-values is averaged and given a weight proportional to the floor area these points represent; the whole floor U-value can then be estimated by summing the weighted mean of the different floor zones. However, this method also requires that a few point measurements are sufficient to characterise these different floor zones as representative of the whole floor.

Delsante (1989) observed a perimeter effect up to 1 metre from the external walls in solid ground floors, though such zoning is not well characterised for suspended ground floors. Using this 1 metre perimeter zone characterisation for the Salford EH, the estimated U-value of the perimeter zone was 1.02 $Wm^{-2}K^{-1}$ (mean of estimated U_p-values in location 1, 9 and 10 to 14); while the mean U-value of the remaining non-perimeter points was 0.69 $Wm^{-2}K^{-1}$, assumed to be representative of the non-perimeter zone. This lead to a weighted whole floor U-value estimate of 0.88 ±0.08 $Wm^{-2}K^{-1}$. The error margin was based on the weighted average of the uncertainty estimates of the point U-values.

4.4.2.3. Area-weighted summation

The total heat-flow through an element can be regarded as the summation of the heat-flow through a number of areas, which can be represented by a 'grid', see *Figure 32.* It is assumed that each point measurement taken is representative of heat-flow through the surrounding area defined by the grid. Weighting for each zone is simply calculated by dividing each zone's area by the whole area of the element. Summing all of these weighted point U-values gives an area-weighted whole floor U-value estimate (U_{wf}), as per *Equation 52.* and shown as derived in *Table 18.* and illustrated in *Figure 32.*

The whole floor estimated U-value error can be estimated in the same way.

$U_{wf} = \sum_{j=1}^{n} U_j \frac{A_j}{A_{wf}}$ - *Equation 52.* , where U_{wf} ($Wm^{-2}K^{-1}$) is the whole floor U-value; $\frac{A_j}{A_{wf}}$ is the weighting factor where A_j in m^2 is the representative floor area assigned to each U-value point (U_j) and A_{wf} is the whole floor area. Index j identifies individual point locations on the floor measured simultaneously and n is the number of point locations observed.

The whole floor error is obtained in the same way, by multiplying the individual point error by the weighting factor $\frac{A_j}{A_{wf}}$.

ASTM (2007a) advises the use of infrared thermography to establish whether the area around each sensor location is similar in order to interpolate to a larger area; as expected "*interpolated values away from sensors are less accurate than measurements obtained at sensor sites*" (ASTM, 2007a). The use of infrared images (see *Figure 31.)* supported the qualitative estimation of areas (A_j) around each sensor as representative of that sensor's U-value (U_j). This procedure lead to the floor area being divided in a grid formation - see *Figure 32*. However, even with many U-value point measurements, dividing the floor area still required a choice between several possible area grid configurations, increasing uncertainty (as noted in Chapter 3.3.4.3.). Different configurations were tested for the Salford EH, especially along the perimeter and for the larger zones around sensors 1, 7, 8, and 9, however this did not affect the estimated whole floor U-values within the two decimals presented here.

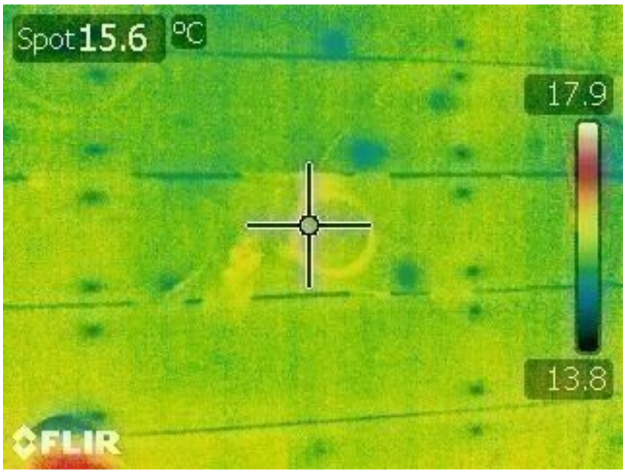

Figure 31. Infrared images can be useful to understand how representative each measurement location is prior to interpolation of each point to a larger area. The image shows a region around an individual sensor.

For the Salford EH, the whole floor U-value estimated by weighted summation is equal to the mean estimated whole floor U-value of 0.83 ± 0.08 $Wm^{-2}K^{-1}$; however this excludes reduced heat-flow through the joists. Accounting for 12% joists and assuming that the heat-flow through all the joists was 21% less than through floorboards, as was found for location 11 in this study, for illustrative purposes this would give an adjusted whole floor U-value of 0.81 ±0.08 $Wm^{-2}K^{-1}$.

	Mean U-value, U_j $Wm^{-2}K^{-1}$	Estimated representative dimensions around each sensor location			**area weighted U** i.e. $U_j * A_j$ $Wm^{-2}K^{-1}$	
		length 1 (mm)	**length 2** (mm)	**A_j, total area** (m^2)		**U/A_{wf}**
Location 1	0.73	800	1775	1.42	1.04	0.08
Location 2	0.72	1000	1200	1.2	0.87	0.07
Location 3	0.66	1200	1200	1.44	0.95	0.07
Location 4	0.61	800	700	0.56	0.34	0.03
Location 5	0.56	400	700	0.28	0.16	0.01
Location 6	0.67	650	1400	0.91	0.61	0.05
Location 7	0.77	650	1400	0.91	0.70	0.05
Location 8	0.81	750	1400	1.05	0.85	0.06
Location 9	0.92	800	1775	1.42	1.31	0.10
Location 10	1.16	750	950	0.7125	0.83	0.06
Location 12	1.03	950	1500	1.425	1.47	0.11
Location 13	1.09	950	700	0.665	0.72	0.05
Location 14	1.18	separately calculated due to bay geometry		0.64	0.75	0.06
Location 15	0.70	500	1400	0.7	0.49	0.04
MEAN U	**0.83**			**13.33**	**11.09**	**0.83**
				A_{wf}, living room floor area		**U_{wf}, AREA WEIGHTED AVERAGE**

Table 18.The table above shows the area dimensions and area grid for each of the point U-values - approximately represented by areas in Figure 32.

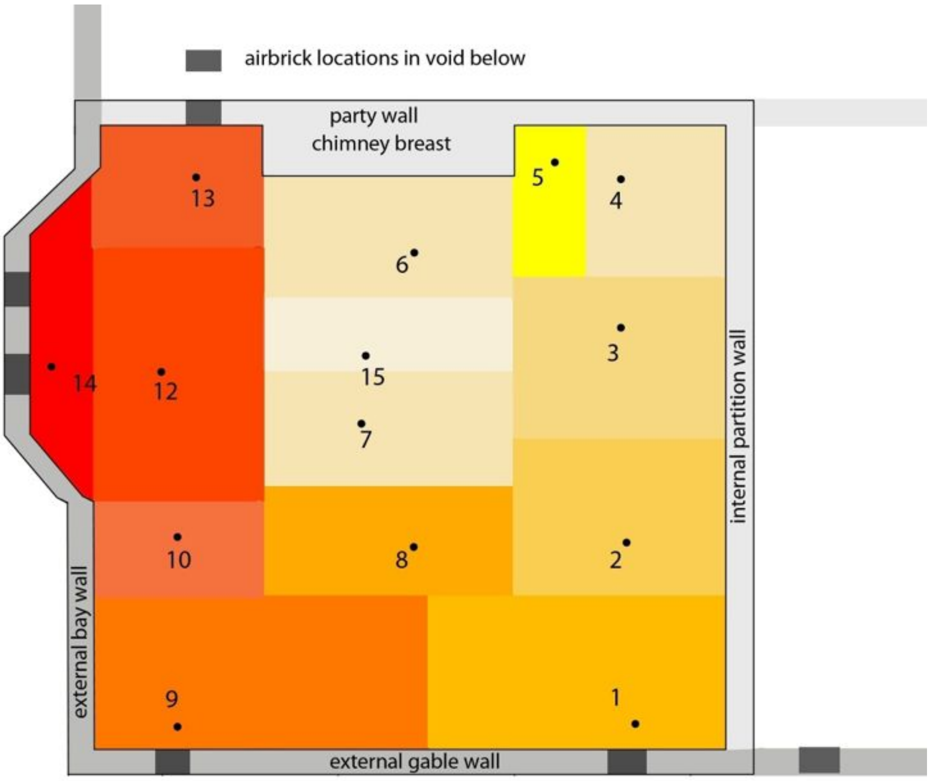

Figure 32. Simplified and approximate representation of the area grid used for weighted summation, whereby each U-value point location is considered representative of the identified area.

4.4.2.4. Comparison between estimated whole floor U-values

Table 19. indicates that whole floor estimated U-values, obtained from different averaging methods, were similar and between 0.83 ±0.08 $Wm^{-2}K^{-1}$ and 0.88 ±0.08 $Wm^{-2}K^{-1}$, with overlapping error margins. Based on those margins - whole floor U-values were estimated between 0.75 to 0.96 $Wm^{-2}K^{-1}$. In the final column in *Table 19.*, the presence of joists was accounted for, based on 12% joist presence obtained from a site survey and based on the 21% reduced U_p-value measured through the joist in location 11. It should be noted that as heat-flow through the joist was measured near the perimeter, it is likely that the joist had a proportionally greater impact on heat-flow reduction than if measured further away from the perimeter. This means that the whole floor U-value after joist adjustment might slightly underestimate the whole floor U-value, however as there were only 12% of joists present, this effect was likely to be minimal on the whole floor U-value.

For the Salford EH floor, there were small differences depending on which point to whole floor U-value estimation technique was used. While it appears unimportant how the average floor U-value was obtained for this data set, for fewer in-situ data and where measurement locations are not evenly distributed, a weighted technique - as set out in Section 4.4.2.3. - is likely to be more appropriate than a mean U-value. The fewer point U-values are used, the less certain the whole floor U-value is. Hence high-resolution measurements are best to estimate a whole floor U-value, for which the weighted summation technique appears most appropriate as it allows an area around each sensor to be taken account of in the whole floor U-value. However even when using weighted summations, there will still be an unknown spatial uncertainty associated with locations of point U-values and whether the chosen locations are representative of the rest of the floor and of the assumed representative areas of the floor.

Investigated point to whole floor estimating methods	**Salford whole floor U-value ($Wm^{-2}K^{-1}$)- excluding joist presence**	**Salford whole floor U-value ($Wm^{-2}K^{-1}$) - including joist presence** (based on location 11)
Mean (see Section 4.4.2.1)	0.83 ± 0.08 (0.75-0.91 $Wm^{-2}K^{-1}$)	0.81± 0.08 (0.73-0.89 $Wm^{-2}K^{-1}$)
Grouping estimated point U-values (<1000 mm perimeter and ≥1000mm from perimeter) (see Section 4.4.2.2)	0.88 ± 0.08 (0.80-0.96 $Wm^{-2}K^{-1}$)	0.86 ±0.08 (0.78-0.94 $Wm^{-2}K^{-1}$)
Area-weighted summation (see Section 4.4.2.3)	0.83 ± 0.08 (0.75-0.91 $Wm^{-2}K^{-1}$)	0.81± 0.08 (0.73 to 0.89 $Wm^{-2}K^{-1}$)

Table 19. Summary table with estimated whole floor U-values obtained from estimated point-U-values for the Salford Energy house, with and without joist presence adjustment

4.4.2.5. Estimating a whole floor U-value with fewer point measurements

Usually, in-situ measuring campaigns are limited by access to equipment and restricted by measurement locations in occupied dwellings due to placement of furniture and occupant activities. Often only a limited number of locations along the external wall perimeter are accessible due to how rooms are used; however as illustrated here, measuring along the perimeter only is likely to significantly overestimate the whole floor U-value.

Considering a hypothetical limited monitoring campaign using - as example - only point U-values in locations 4 and 5 on the Salford EH floor, the estimated mean whole-floor U-value would be 0.59 ±0.06 $Wm^{-2}K^{-1}$, excluding joist presence. This is much lower than the estimated whole floor U-value of 0.83 ±0.08 $Wm^{-2}K^{-1}$, based on the area-weighted summation of 14 observed points. Similarly, observing heat-flow in locations 10 and 12 would lead to an overestimated whole floor U-value of 1.10 ± 0.11 $Wm^{-2}K^{-1}$; both these estimates are outside the margins of error. *Figure 33.* highlights the mean U-values obtained from pairing just 2 point U-values within the error margins of the whole floor mean (in red zone) - indicating that a large number of U-values estimated by averaging just two point-measurements (about 70%) would under- or over-estimate the whole floor U-value.

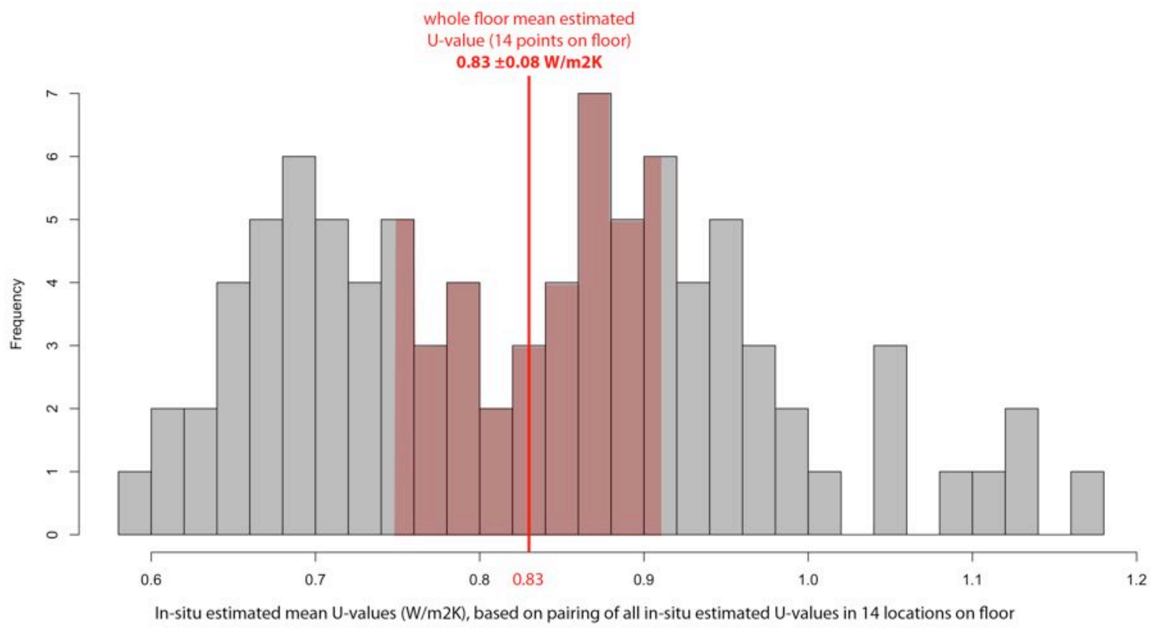

Figure 33. Histogram of the 91 paired U-values; about 30% of the paired values would be within the margins of error of the whole floor estimated U-value; the red line indicates the whole floor estimated U-value, while the red bars indicate the U-value distribution within the error margins of the whole floor U-value.

Appendix 4.A. lists the 32 paired locations (or 30% of the pairs) where the mean paired U-value overlapped with the overlapping error margin of the whole floor U-value, i.e. between 0.75 and 0.91$Wm^{-2}K^{-1}$. Only one pairing combination (location 1 and 9 along the perimeter (and above airbricks)) lead to an exact match with the whole floor U-value. Generally, for the semi-detached Salford EH, it appeared that one perimeter location and an internal floor location were more likely to give a better estimate of the whole floor U-value. Note that location 13 was an anomaly due to the airbrick to the neighbouring house. Some combinations of middle of the floor with gable perimeter wall locations might also provide close whole floor U-value matches for this study, as do two middle of the floor locations combined; though note that measuring in the middle of the floor is not a practical location in occupied dwellings.

Clearly, observing just one or two point locations on a construction element such as a floor - which is subject to a large spread of heat-flow as illustrated by the Salford EH findings - means that the estimated whole floor U-values might be over- or under-estimated depending on where those point U-values were measured. Random selection of measuring locations is highly likely to lead to a poor representation of the whole floor U-value. When a large spread of heat-flow across a building element is present it is challenging to define a 'representative' or 'typical' area where to undertake these few point measurements. While several locations combined could construct an average U-value that is within the whole floor U-value margin, this was only possible by measuring at high-resolution to give a sufficient number of measured locations to combine. As such, deriving a whole floor U-value based on a single or few point measurements has unknown and possibly significant uncertainties associated with it. Increased purposeful monitoring of many points across the surface will reduce uncertainty of estimating the whole floor U-value under those measuring conditions. The spread of U_p-values across a floor needs to be represented by a sufficient number of in-situ point measurements, and comparison of low-resolution with high-resolution data is likely to be problematic.

4.4.3. Whole floor U-values and comparison to models and other sources

As discussed in Section 4.4.2, obtaining an estimated whole floor U-value is useful for comparison with U-values estimated from models; comparisons between the two are presented in this section, taking the living room bare floorboarded floor as being representative of the entire Salford EH floor.

For the Salford EH, the floor U-value from models was estimated between 0.59 and 0.68 $Wm^{-2}K^{-1}$ using the ISO-13370 model (BSI, 2009b) as described in Chapter 2 with joist presence of 12% and depending on assumed wind-speeds (between 1-5 m/s) and concrete ground conductivity between 1.3 and 1.9 $Wm^{-1}K^{-1}$ (as per CIBSE (2006)); and as described by five models in *Table 20.* Other characteristics and inputs required for the models are listed in *Table 21*. for both the Salford EH and the 2012 pilot study. The model values are based on data that could be recorded while other inputs, such as assumed material conductivities of floorboards, foundation walls and the characteristic of the concrete subfloor as well as wind-speeds were based on assumptions. In the Salford EH no wind-speed was simulated, hence the wind-speed was expected to be small, but there might still be air movement effects from the chiller plant for example. Hence standard wind-speed model assumptions were tested alongside lowered wind-speeds to 1m/s. Using RdSAP (BRE, 2011) and CIBSE (2006) assumptions (instead of using surveyed Salford EH characteristics as typical inputs), estimated model outputs were between 0.60 and 0.73 $Wm^{-2}K^{-1}$(Models 1 to 3); this excluded joist presence as the assumed models' default thermal resistance input for floor deck was used. When the RdSAP and CIBSE models were adapted for 1m/s wind-speed and actual surveyed airbrick openings and other surveyed inputs and including joist presence, the modelled outputs dropped to between 0.58 $Wm^{-2}K^{-1}$ and 0.71 $Wm^{-2}K^{-1}$ - see *Table 20.,* Models 4 and 5. The superseded CIBSE-1986 model lead to higher U-value estimates than the current models; with a mean U-value of 1.11 $Wm^{-2}K^{-1}$ and especially model 4 was more similar to the whole floor in-situ measured U-value. Note that wind-speed input assumptions have a significant influence on CIBSE-1986 model outputs - see in Section 4.4.3.1. Yet at present it is unclear what the wind-speed is at airbrick height and whether models accurately reflect this.

Model	Iterations - input assumptions (as per Table 21.) * Excludes joist presence	**Current model** **Outputs ISO-13370** - as per Salford EH survey ($Wm^{-2}K^{-1}$)	**Current model** **Outputs RdSAP** - as per *Table 21.*, using RdSAP input assumptions ($Wm^{-2}K^{-1}$)	**Current model** **Outputs CIBSE-2015** - as per *Table 21.*, using CIBSE input assumptions ($Wm^{-2}K^{-1}$)	**Superseded model** **Outputs CIBSE-1986** - as per *Table 21.*, and using CIBSE 1986 assumptions as described in Section 2.3 and as per survey. ($Wm^{-2}K^{-1}$)
1	Concrete sub-floor conductivity input of 1.9 $Wm^{-1}K^{-1}$; windspeed based on RdSAP assumption of 5 m/s	0.68	0.72*	0.73*	1.27
2	As Model 1 but concrete sub-floor conductivity input of 1.6 $Wm^{-1}K^{-1}$	0.64	0.69*	0.69*	1.20
3	As Model 2 but concrete sub-floor conductivity input of 1.3 $Wm^{-1}K^{-1}$	0.60	0.60*	0.64*	1.13
4	As Model 3 but windspeed assumed to be 1 m/s after CIBSE-1986; airbrick opening & other inputs to match survey (i.e. 0.00077 m^2/m) in RdSAP & CIBSE 2015 models (others already matched)	0.59	0.58	0.61	0.87 *(0.75 with 0m/s wind-speed)*
		Same predicted U-value with 0m/s wind-speed			
5	As Model 4, but concrete sub-floor conductivity input of 1.9 $Wm^{-1}K^{-1}$ as per model 1	0.67	0.66	0.71	1.08 *(0.99 with 0m/s wind-speed)*
MEAN OF ALL MODELS ($Wm^{-2}K^{-1}$)		**0.64**	**0.65**	**0.68**	**1.11**

Table 20. presents different Salford EH models and different model input assumptions, alongside modelled outputs. Note that the CIBSE-1986 model is superseded by the CIBSE-2015 model but has been included here for comparison purposes. R_{Si} of 0.17 m^2KW^{-1} has been assumed throughout. Note that Model 4 and 5 with 0m/s wind-speed and no airbrick opening (i.e. closed airbricks) give the same model output estimates (to two decimals) as with 1m/s wind-speed apart from the CIBSE-1986 model outputs, which reduce further and are noted in brackets in italics. Excludes joist presence*

Figure 34. plots the mean modelled U-values outputs described in *Table 20.* and U-values derived from literature alongside the in-situ estimated whole floor U-values (derived from area-weighted summation - see Section 4.4.2.). Overall, the divergence between the Salford EH in-situ estimated whole floor U-value and the U-value estimates from current models was between 10% and 28%, depending on model used and input assumptions. Given the uncertainties in in-situ measurements and model input assumptions, both CEN (1996) and ISO-9869 (BSI, 2014) only regard significant disparities to be greater than 20% between measured and modelled U-values. In reality, because of error margins around the in-situ U-values, and depending on which assumptions were used in models, potential disparities might be small or almost non-existent (i.e. < 20%). *Figure 34.* illustrates that in general, the current models appear to underestimate the in-situ estimated whole floor U-value of the Salford EH and error margins do not overlap. Contrary to this, the superseded CIBSE-1986 model gave U-value estimates 7% to 36% above the in-situ measured whole floor U-value.

Overall for the *current* models, Model 1 is closer aligned with the in-situ estimated whole floor U-value, however Models 1, 2 and 3 assumed 5m/s wind-speed (RdSAP recommended (BRE, 2011)); yet this is unlikely to be reflective of the low windspeed encountered in the Salford EH (though this was not measured). Nor do these three models account for the actual airbrick openings and other surveyed variables of the Salford EH in the CIBSE-2015 and RdSAP models. Model 4 and 5 were adjusted for these differences to better reflect the Salford EH conditions, but as expected, adjusting the wind-speed (1m/s) and airbrick openings widens the disparity between modelled and measured U-values for the current models. However, the superseded CIBSE-1986 Model 4 output is closer to the in-situ measured value of $0.81 \pm 0.08 Wm^{-2}K^{-1}$, taking joist presence into account. However as with the other models there is uncertainty around the input assumptions and it is unknown whether this close alignment is accidental or due to accurate input assumptions and a better model fit.

As discussed in Section 4.2.3., the estimated modelled U-value of the pilot study floor also appeared to underestimate in-situ U-values, however the latter was based on just two point locations and lead to significant uncertainty with regards to estimating the whole floor U-value for comparison with models. As discussed in Chapter 3 and in Chapter 2.4., care must be taken with comparisons and generalisations between models, literature and in-situ estimated U-values. Furthermore, the pilot study whole floor U-value is also unlikely to be comparable to the in-situ estimated whole floor U-value of the Salford EH due to the low-resolution monitoring and the many different variables between both studies, including *P/A* and to what extent the Salford EH floor heat-flow reflects that of real houses in real situations due to different variables - as described previously in Section 4.3.1.

In summary, additional field studies and a larger sample of in-situ measured U-values of floors at high resolution are required to investigate whether the disparity of current models and closer alignment with the superseded CIBSE-1986 model is reflected in the wider housing stock also. These results also indicate that without further high-resolution in-situ measurements, it is difficult to know whether the current models are an improvement of the superseded CIBSE-1986 model or not.

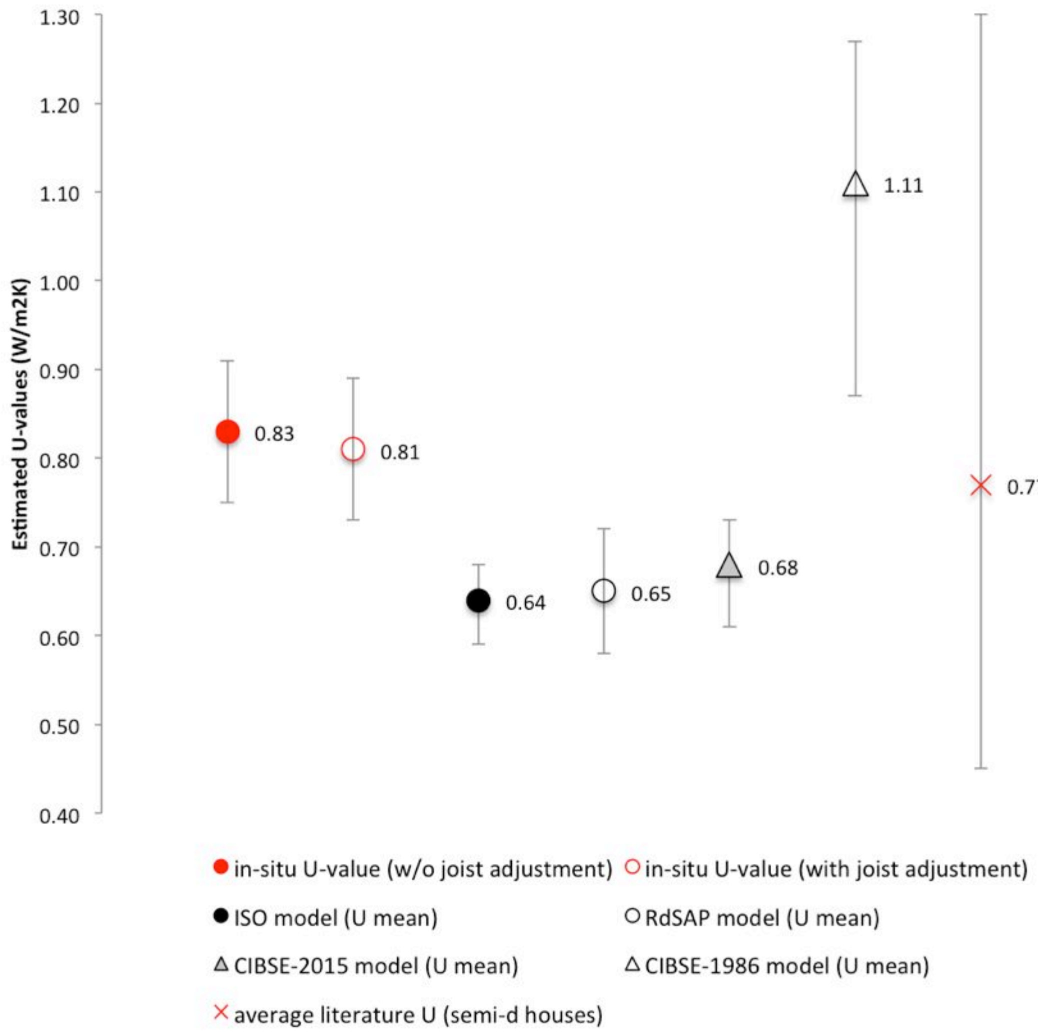

Figure 34. Comparison between differently estimated U-values for the Salford EH: differently in-situ estimated whole floor U-values and mean literature and mean modelled U-values estimated with model assumptions described in Table 20. Model error margins were derived from the minimum and maximum U-value outputs around the mean U-value from Table 20.; the literature error margins were based on the extreme values encountered in literature. In-situ U-value error margins were derived as previously described in Section 4.4.2.

Variables	Salford EH characteristics	2012 Pilot case study	RdSAP / CIBSE assumptions (BRE, 2011, CIBSE, 2015)
	based on site survey or as otherwise stated		
Perimeter (*P*)	16.34 m (for CIBSE 1986 model: simplified inputs: width (b) 3.78 m; l_f length= 7.5m)	12.94 m (width (b)= 4.55m)	
Total Floor area (*A*)	28.46m^2	55 m^2	
P/A	0.57 m/m^2	0.24 m/m^2	
B' = A/0.5P	3.48 m	8.5 m	
Airbrick ventilation opening area	0.0126 m^2	Total 0.0147 m^2 (incl. unintended air gaps of 0.0094 m^2)	
Total ventilation opening area per metre exposed perimeter	0.00077 m^2/m	0.0011 m^2/m	Assumed 0.0030 m^2/m in RdSAP; or 0.0015 m^2/m in CIBSE
Joist dimensions	0.045 m x 0.190 m	0.050 m x 0.100 m	
Joist spacing (centre to centre)	~ 0.35-0.40 m c/c	0.31 m- 0.39m c/c	
% Joist vs floor board	12%	~12%	
Floor board thickness (19mm)	0.019 m	0.019 m	Assumed R_f = 0.2 m^{2}KW^{-1} (RdSAP & CIBSE)
Softwood conductivity *k*	0.13 Wm^{-1}K^{-1} (Anderson, 2006)	0.13 Wm^{-1}K^{-1} (Anderson, 2006)	
soil conductivity (λ_g)	Concrete base - 1.3-1.9 Wm^{-1}K^{-1}(CIBSE, 2015)	Clay, (GLA, 2004); assumed 1.5 W/mK (CIBSE, 2015)	
Foundation wall thickness (d_w)	0.22 m	0.22 m	
Thermal transmittance foundation wall U_w	1.7 Wm^{-2}K^{-1} (CIBSE, 2015)	1.7 Wm-2K-1 (CIBSE, 2015)	U_w = 1.5 Wm^{-2}K^{-1} in RdSAP; 1.7 Wm^{-2}K^{-1} in CIBSE
Height of floor surface above external ground level (*hf*)	0.26m (in this case also roughly equal to void depth)	0.25m (in this case also roughly equal to void depth)	Assumed h = 0.3 m
R_{Si}	0.17 m^{2}KW^{-1} (CIBSE, 2015)		
R_{Se}	0.04 m^{2}KW^{-1} (CIBSE, 2015)		
average windspeed at 10 m (*v*)	Unknown for EH; assumed to be between 0 to 5 m/s, based on RdSAP assumed average as top limit.	4.5 m/s; N17 average wind-speed at 10m high (RRR, 2015)	5 m/s in RdSAP; 3 m/s in CIBSE as average windspeed
Wind shield factor f_W	lowest assumed: 0.02 (BSI, 2009a), as protected	0.05 (BSI, 2009a)	Assumed 0.05 in RdSAP; range of 0.02/0.05 and 0.1 depending on exposure in CIBSE and ISO-13370

Table 21. Salford EH and 2012 pilot case study house characteristics and model assumptions.

4.4.3.1. Sensitivity analysis

A limited and simplified sensitivity analysis was undertaken of the ISO-13370 suspended floor U-value model[10] and the CIBSE-1986 model, using the floor characteristics of the Salford EH for illustrative purposes. A sensitivity analysis is a study of the variation of input variables and their effects on the model output variation (Saltelli, 2008), in this case floor U-values. Different sensitivity analyses can be conducted, each with their advantages and limitations. In this research, a *screening sensitivity analysis* was conducted (Saltelli, 2008), which enabled the qualitative evaluation and understanding of the impact of changing input parameters on output variability. This allowed the isolation of the most significant variables affecting the model U-value outputs (Saltelli, 2008). Only one variable at a time (OAT) was changed with all the other variables constant to test the impact of each variable on the estimated modelled U-value output in turn. Minimum and maximum inputs were used to give value ranges (*control experiment* (Saltelli, 2008)) and these were obtained from literature with - where applicable - sources noted on *Figures 35* and *36*; values in between were modelled at regular intervals. A limitation of screening is that no quantitative ranking of the variables is obtained nor a probability distribution of the range of the variables as for example in *local sensitivity analysis* (e.g. differential analysis) and *global sensitivity analysis* (e.g. Monte Carlo analysis) (Saltelli, 2008). A limitation of OAT sensitivity analysis is that it relies on standard values per variable and simultaneous interactions of changing variables and evaluation of the impact on model outputs are excluded (Saltelli, 2008). Screening only allows the evaluation of the main effects and is considered an effective way to do so (Saltelli, 2008). OAT screening was considered appropriate given the purpose of the sensitivity analysis was the understanding and comparison of the important variables in both models.

The graphs in *Figure 35. and Figure 36.* illustrate the impact of the ISO-13370 and CIBSE-1986 models' assumed inputs and their effect on modelled floor U-values. For model inputs and floor characteristics, see *Table 21*.

[10] The ISO-13370 model was used here for a simple sensitivity model given that ISO-13370 is the basis of the current RdSAP and CIBSE 2015 models.

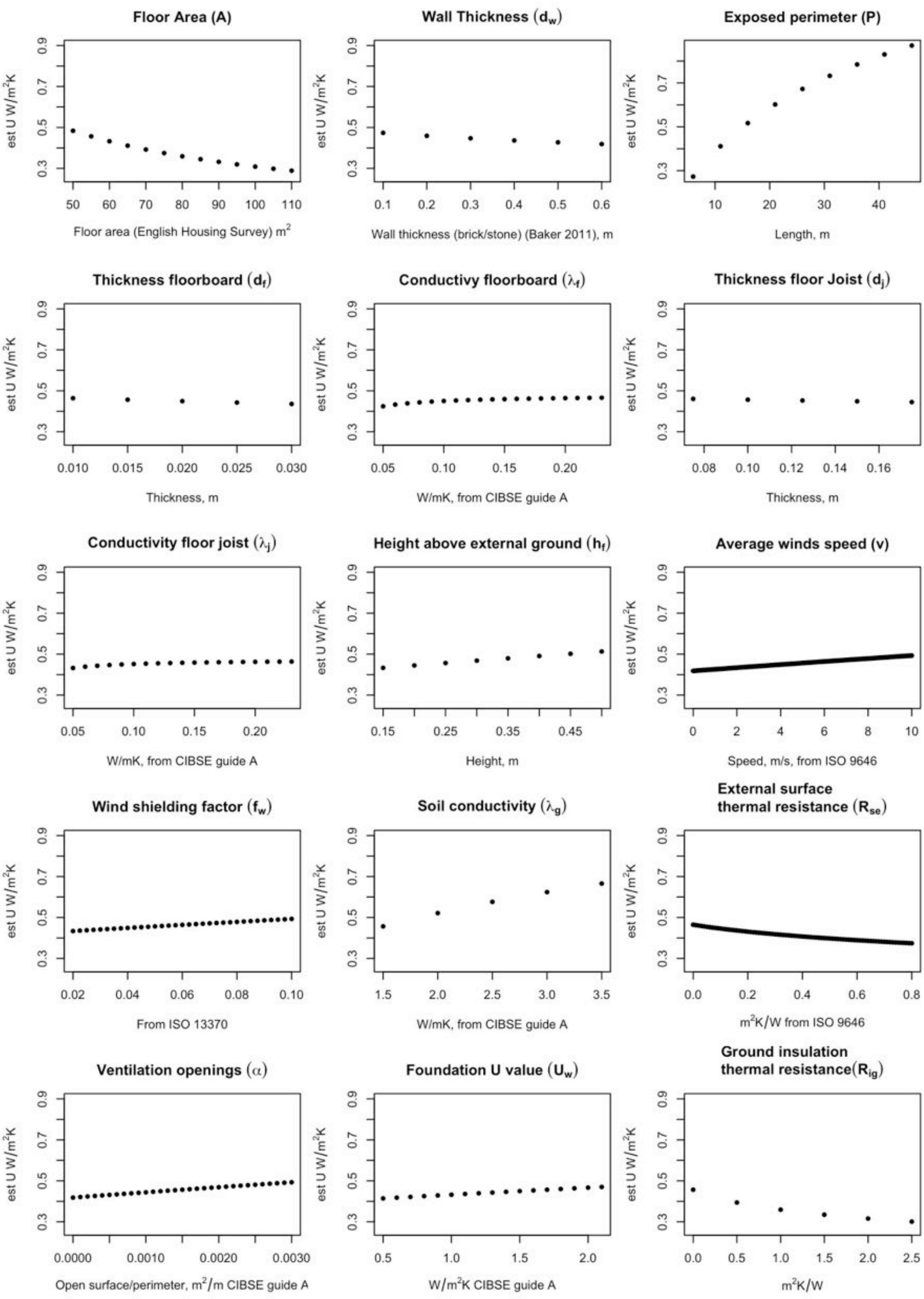

Figure 35. Sensitivity analysis of the ISO-13370 model variables, changed one at a time; where no source noted, values were estimated by author based on case studies. From this analysis, the floor perimeter (P), the ground conductivity (λ_g) and the floor area (A) were the variables with the greatest impact on modelled floor U-values.

The ISO-13370 sensitivity analysis suggested that with the input assumptions, the floor perimeter (*P*) and the ground conductivity (λ_g) variables had the widest range of modelled floor U-values alongside the floor area (*A*). Increasing the exposed perimeter (*P*) from terraced house to detached house lead to increased estimated floor U-values from about 0.27 to 0.87 $Wm^{-2}K^{-1}$. As expected the floor U-value was negatively correlated with floor area *(A)* (i.e. the larger the floor area the lower the U-value) and positively correlated with the height of the floor (h_f) above the ground and the exposed floor perimeter zone (*P*) (i.e. the greater the exposed floor perimeter, the greater the modelled heat-flow output). As expected, other negative correlations were found with foundation wall depth (d_w) and joist depth (d_j) and external and internal surface thermal resistances (i.e. R_{Se}), though all with limited individual impact on the final U-value according to the model. Positive correlations were found for floor board conductivity (λ_f), joist conductivity (λ_j), windspeed (*v*), f_w as protection from the wind and airbrick opening (α) and foundation wall U-value (U_w). Particularly increased windspeed (*v*, from 0 to 10 m/s) and airbrick openings (α, from 0 to 0.0030 m^2/m) had a noticeable, though relative small effect on floor U-values, increasing the U-value from 0.42 to 0.49 $Wm^{-2}K^{-1}$. Some linear heat-flow effects were suggested by the model: for example, wind-speed *(v)* and wind protection (f_w), airbrick opening (α), and - as expected - foundation wall U-value (U_w) and material depths.

As expected, similar trends were observed in the superseded CIBSE-1986 model - see *Figure 36.* but gives higher U-values and only two modelled variables were linear: soil conductivity (λ_g) and floor thermal resistance *(R_g)*. For the CIBSE-1986 model, the ventilation opening area (α) and assumed wind-speed *(v)*, followed by ground conductivity (λ_g) and area of floor (A_f) are the variables which give the widest range of U-values with the assumed inputs. The effect of wind-speed *(v)* and airbrick ventilation opening area (α, based on length *(l_f)*, not exposed perimeter), had a much greater impact on the CIBSE-1986 model outputs than on the ISO-13370 model outputs and it lead to a wider range of floor U-values for the CIBSE-1986 model with the same input assumptions (0.8 to 1.4 $Wm^{-2}K^{-1}$ compared to < 0.5 $Wm^{-2}K^{-1}$ for the ISO-13370 model). While the CIBSE-1986 U-value model gives greater importance to the ventilation opening area (α) and wind-speeds *(v),* it is unclear how representative this is of actual and assumed inputs and performance but this might partially explain some divergence between the models.

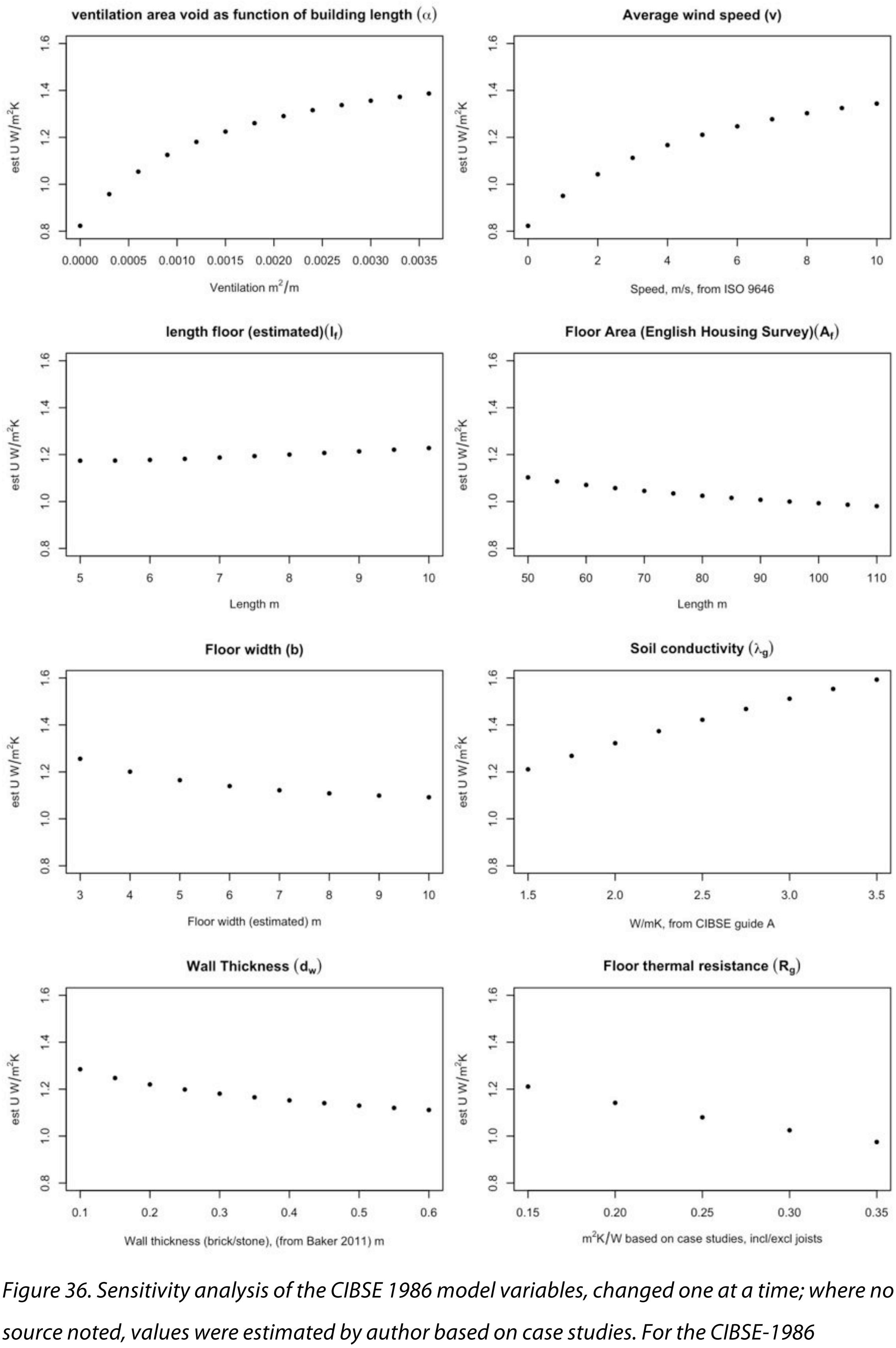

Figure 36. Sensitivity analysis of the CIBSE 1986 model variables, changed one at a time; where no source noted, values were estimated by author based on case studies. For the CIBSE-1986 analysis, the ventilation opening area (α), assumed wind-speed (v) and ground conductivity (λ_g) were the variables with the greatest impact on modelled floor U-values.

4.4.3.2. Comparison to Building regulations

For the renovation of ground floors, current building regulations approved document Part L1B, '*Conservation of fuel and Power in Existing dwellings*' applies in England, with similar regulations in Scotland, Wales and Northern Ireland. This means that for the restoration or upgrade of ground floors, minimum standards are recommended: regulations require the design U-values in the upgraded ground floor in dwellings to be no greater than 0.25 $Wm^{-2}K^{-1}$ in all UK regions (NBS, 2015, SBSA, 2015, Government, 2014, DFPNI, 2012). As expected, the recommended insulation standard is significantly better performing than the Salford estimated in-situ whole floor U-value of the uninsulated floor and at least twice as good as the Salford EH modelled U-values of the uninsulated floor.

4.4.3.3. Comparison to literature and other in-situ monitoring studies

Table 2. in Chapter 2.4.1. presents literature U-values for semi-detached dwellings, which range between 0.70 $Wm^{-2}K^{-1}$ and 1.30 $Wm^{-2}K^{-1}$ and the average of the sources was 0.77 $Wm^{-2}K^{-1}$ as plotted in *Figure 34.* in Section 4.4.3. This mean literature U-value is similar to the estimated in-situ measured whole floor U-value for the Salford EH of 0.81±0.08 $Wm^{-2}K^{-1}$ (taking into account presence of joists - as per discussion in Section 4.4.2.).

As discussed in Section 2.4.2., only a few in-situ measured U-values could be traced for suspended timber ground floors in the UK; for semi-detached dwellings U-values estimated from in-situ measurements ranged from 0.69 to 2.4 $Wm^{-2}K^{-1}$, based on one or two point measurement locations only and indicating some overlap with the Salford EH in-situ measured point U-values. Miles-Shenton (2011) measured one point U-value location in the perimeter zone and one in the middle of the floor and - as also observed here - found that the U_p-value in the bay was greater than in the middle of the floor. The few in-situ point measurements available (Chapter 2.4.2, *Table 3.)* highlight the wide variation of U-values estimated in different locations in different dwellings in the field. It also appears that the point U-values observed in the perimeter in other studies were generally higher than those observed along the perimeter zone in the Salford EH.

This might be caused by a combination of the following:

- Differences in environmental conditions or physical form and materials between the Salford EH and other studies. For example, the lack of replicated wind in the Salford EH, which is likely to reduce the rate of heat-flow, in addition to other Salford EH constraints as discussed in Section 4.3.1. Differences between the case-study buildings include the sub-floor characteristics, ventilation rates, floor finishes, void depths, wall thermal performance and environmental and site conditions. These variables affect measured floor U-values differently hence comparison between findings from different studies is challenging.
- The large spread of in-situ point U-values observed across the floor in the Salford EH study, highlighted that a few point measurements were unlikely to lead to valid U-value comparisons between studies as each point location is specific to that dwelling and study. Using low-resolution point measurements on the floor to compare to a whole floor U-value from high-resolution measurement in another study makes comparisons challenging.
- Differences in measurement and analysis methods further challenge the comparison between estimated floor U-values presented by different sources. For example, placement of temperature sensors is not the same in each study; often it is undisclosed exactly at which height temperatures are measured. If air temperatures in rooms are inhomogeneous this leads to vertical temperature gradients, affecting U-value estimates as they depend on the temperatures measured, as discussed in Section 4.4.5.

4.4.4. Impact of closing of air bricks on U-values

This section supports evidence for hypothesis H3. ("*There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks.*"). The impact of sealing airbricks on U-values was observed whereby all of the 7 airbricks of the Salford EH were closed for 7 days while 15 point U-values were measured. Due to data-logger memory failure, location 7 and 8 were analysed from May 4^{th} to May 8^{th}, over a 5 day period, while all other locations on the floor were analysed from May 7^{th} to May 10^{th} over a 3 day period; internal and external chamber conditions were kept the same. Afterwards the airbricks were opened up while continuing to characterise the floor heat-flow for another 5 days - results of the unsealed airbrick U_p-values were presented in Section 4.4. and are compared here to the estimated U-values with sealed airbricks. Error margins were estimated after *Equation 49.*, but for ventilated/unventilated floor U-value comparisons, errors were estimated from *Equation 50. Figure 37.* illustrates the closing of air bricks during the observed experiment.

Figure 37. Sealing of the airbricks of the Salford Energy House.

As expected, and illustrated by *Figure 38.* and *Table 22.,* the observed U_p-values reduced with reduced void ventilation: on average the whole floor U-value (based on area-weighted summation) reduced by around 17% from 0.81±0.08 $Wm^{-2}K^{-1}$ to 0.67±0.06 $Wm^{-2}K^{-1}$ with airbricks closed (including joist presence)[11]. Similar results were observed by Tsongas (1994) who reported a 20% increase in thermal resistance after airbricks were sealed.

[11] For the sealed airbricks, the joist U-value in location 11 was 22% lower compared to nearby location 10, similar as with unsealed airbricks.

The current models (Models 4 and 5 - assuming 0m/s windspeed and no airbrick opening (i.e. closed airbricks)) give the same model output estimates (to within two decimals) as with 1m/s wind-speed, while the CIBSE-1986 model outputs reduce further - see *Table 20.* in Section 4.4.3. The CIBSE-1986 model outputs estimated an 8% to 14% reduced floor U-value if based on no airbrick openings and 0m/s wind-speed and Model 4 is a relatively close match to the in-situ estimated whole floor U-value with sealed airbricks (CIBSE-1986 Model 4: 0.75 $Wm^{-2}K^{-1}$). However, it is unknown whether this close alignment is accidental or due to accurate input assumptions and a good model fit - as also noted previously.

As *Figure 38.* indicates and in general, differences in the same U_p-values were observed outside the margins of measurement uncertainty. As expected, increased airflow in the void through open airbricks was a driver of heat-transfer and also increased the spread of U_p-values across the floor.

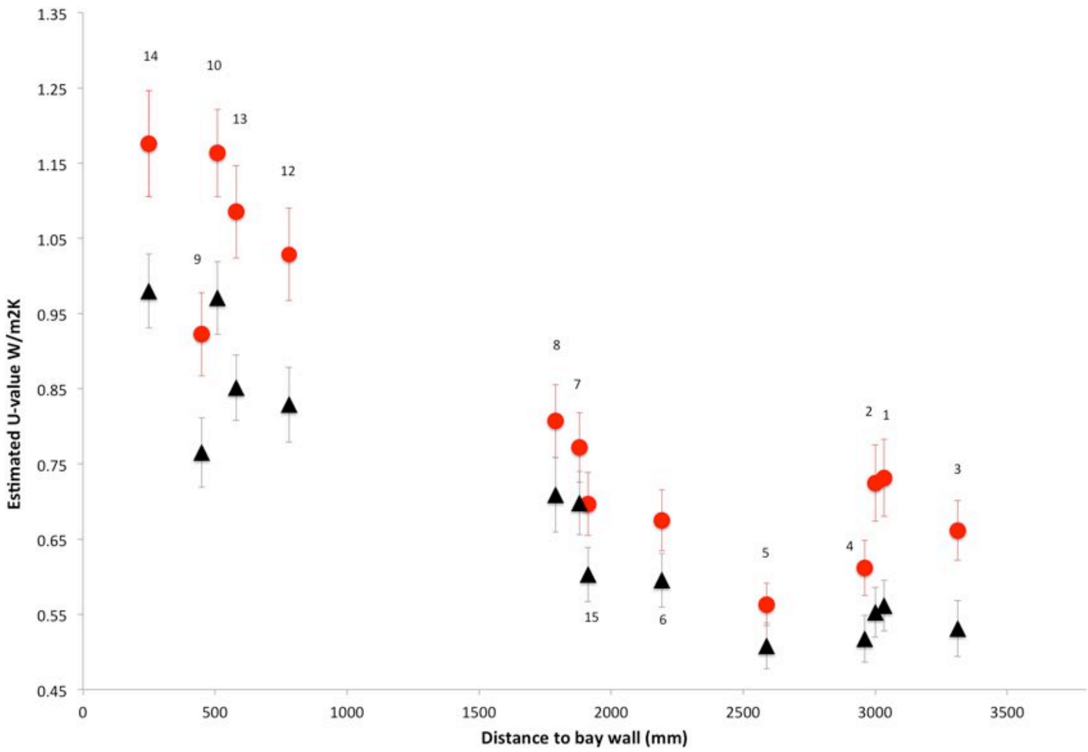

Figure 38. Comparison of all 14 point locations with airbricks open (red data points) or closed (black data points and as a function of the distance to the bay wall. Numbers indicate point locations on the floor; error margins in accordance with Equation 50.

Sensor locations	U-value open airbricks (hourly, outliers removed) ($Wm^{-2}K^{-1}$)	± final error open airbricks ($Wm^{-2}K^{-1}$)	U-value sealed airbricks (hourly) ($Wm^{-2}K^{-1}$)	± final error sealed airbricks ($Wm^{-2}K^{-1}$)	% reduction from open airbricks
HF1	0.73	0.07	0.56	0.05	23
HF2	0.72	0.08	0.55	0.05	24
HF3	0.66	0.06	0.53	0.05	20
HF4	0.61	0.06	0.52	0.05	15
HF5	0.56	0.05	0.51	0.05	10
HF6	0.67	0.06	0.60	0.06	12
HF7	0.77	0.07	0.70	0.07	10
HF8	0.81	0.08	0.71	0.07	12
HF9	0.92	0.09	0.77	0.07	17
HF10	1.16	0.11	0.97	0.09	17
HF12	1.03	0.10	0.83	0.08	19
HF13	1.09	0.11	0.85	0.08	22
HF14	1.18	0.11	0.98	0.09	17
HF15	0.70	0.07	0.60	0.06	13
HF11 (joist)	0.92	0.09	0.76	0.07	24

Table 22. Summary table showing estimated point U-values with airbricks open and closed, and percentage drop in U-value when closed (final column). Perimeter point U-value locations highlighted in red.

A paired Wilcoxcon test of the 14 point measurements supported hypotheses H3: i.e. the observed U-values differed significantly between the open and closed airbrick monitoring periods (Mann–Whitney U = 105, n1 = n2 = 14, $P < 0.05$ (0.0001221), paired). From a statistical viewpoint, this means that the observed differences in U_p-values between decreased and increased ventilation are significant, based on the 14 point measurements across the Salford EH floor. Similar results were obtained when including the point U-value in joist location 11. Blocking up of the airbricks slightly reduced the variability of the U_p-values across the floor surface - as illustrated by *Figure 38.* and *Figure 39.* which illustrate that the increased U_p-values in the perimeter zone were less pronounced. However an unpaired Wilcoxcon test - in support of hypotheses H1 - suggested that the perimeter versus non-perimeter U_p-values still significantly differed (Mann–Whitney U = 44, n1 =6; n2 = 8, $P < 0.05$ (0.007992), unpaired). The estimated mean U-value of the 6 perimeter located points was 0.83 ±0.08 $Wm^{-2}K^{-1}$ which was about 28% greater than the estimated mean of the non-perimeter zone U-values (0.59 ±0.06 $Wm^{-2}K^{-1}$).

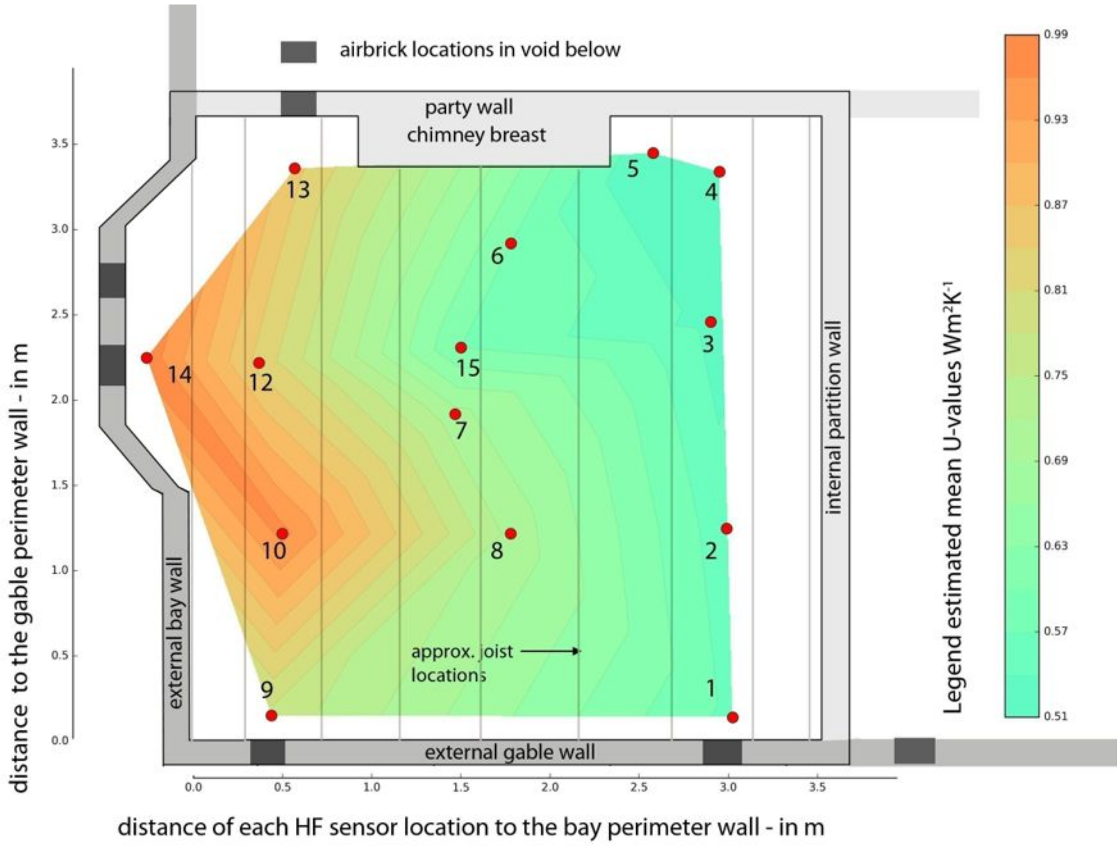

Figure 39. Individual point location U-values with airbricks closed and linear interpolated U-values as a function of both bay (X-axis) and gable (Y-axis) wall distances with airbricks closed. Note that this diagram aids visualisation of trends of floor U_p-values in the Salford EH living room but is not intended to provide a prediction of U-values between measurement points; no account is taken of structural factors, such as floor joists and only values between points are estimated (hence white zones between point locations and room boundaries).

The largest reductions in U_p-values with sealed airbricks were observed for monitored locations near the airbrick below location 1. U-values in locations 1 to 4 were measured between two parallel joists in line with the airbrick below location 1 (as described in Section 4.4.2.), providing clear airflow and air movement from the airbrick in location 1 further back into the void to location 4 between these two joists. Blocking up of the airbricks had a significant impact on all of the estimated point-U-values between these joists: in location 1 and 2, large reductions of 23% and 24% respectively were observed; it is unclear however why this area observed the greatest U-value reduction from sealed airbricks.

As expected, the observed differences in U_p-values were generally greater along the perimeter than further away from the perimeter - as illustrated by the percentage drops in *Figure 40. (overleaf)* and in *Table 22.*

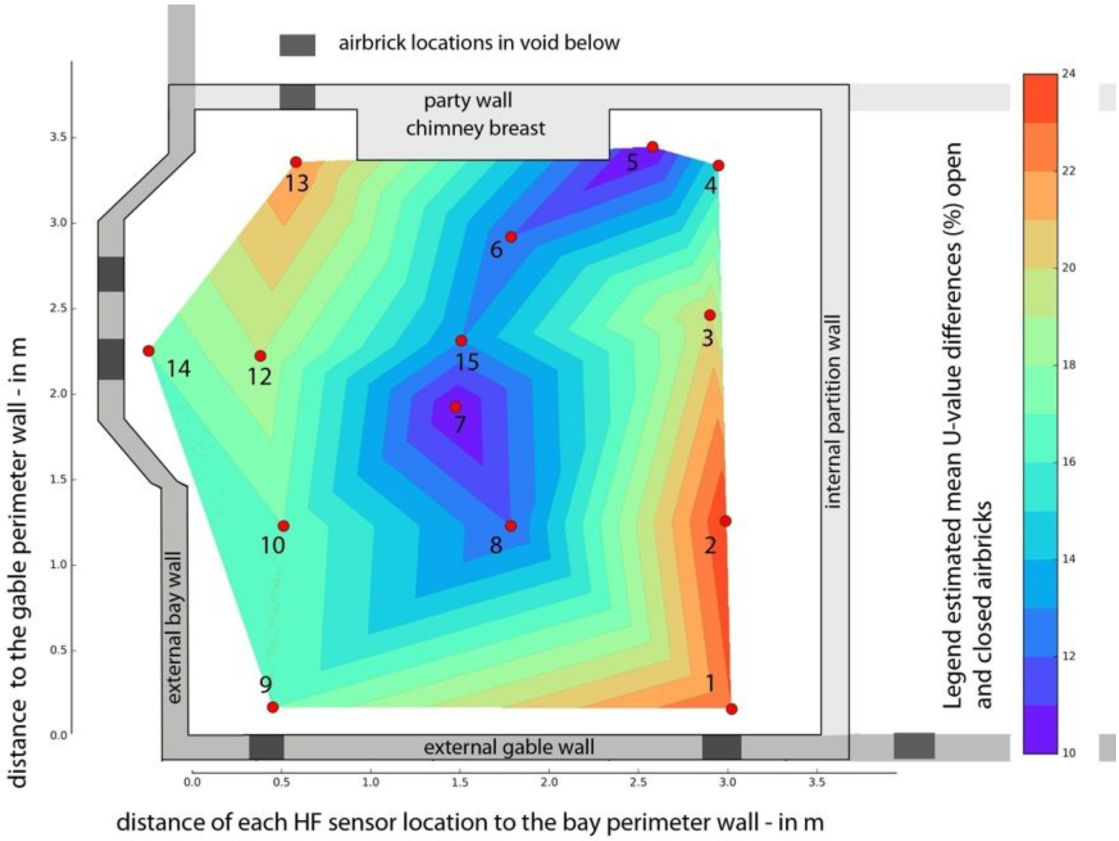

Figure 40. presents individual point location U-value differences and linear interpolated U-value differences in % between airbricks open and closed as a function of both bay (X-axis) and gable (Y-axis).

Along the perimeter, U_p-values were reduced by between 17% and 23% with sealing of airbricks, while point U-values in the middle of the floor (locations 7 and 15) and furthest away from the perimeter (location 4, 5 and 6) were between 10% to 15% lower compared to the ventilated void U-values. Sealing of the airbricks lead to marginally increased surface temperatures by on average 0.45ºC along the perimeter but no significant differences were observed in the non-perimeter zone over the monitored period; this might possibly be explained by the distance away from the airbricks for these locations.

The opening of the airbricks can clearly be seen from *Figure 41.* for location 9 due to the reduced thermal resistance of the floor when opening up the airbricks: there was a clear increase in heat-flux *q* (black line) once the airbricks were opened up alongside a decrease in the surface temperature (grey line), leading to a smaller *ΔT* to the external chamber temperature, which remained constant. *Figure 41.* also indicates a slight upward trend of *q* during the sealed airbricks period and in the first few days after opening up the airbricks; this might be explained by the impact of the airbrick changes on the thermal mass equilibrium of the ground and void surfaces and/or this might be related to airbrick sealing issues (seals had to be re-fixed on a few occasions).

Further research would be required to understand the effect of closing of airbricks on the ground's thermal equilibrium in more detail. Note that the peaks on this graph are explained by researcher influence when collecting data; the airbricks-open data were treated with Chauvenet's Criterion as discussed in Section 4.3.5., while untreated for the airbricks-closed data.

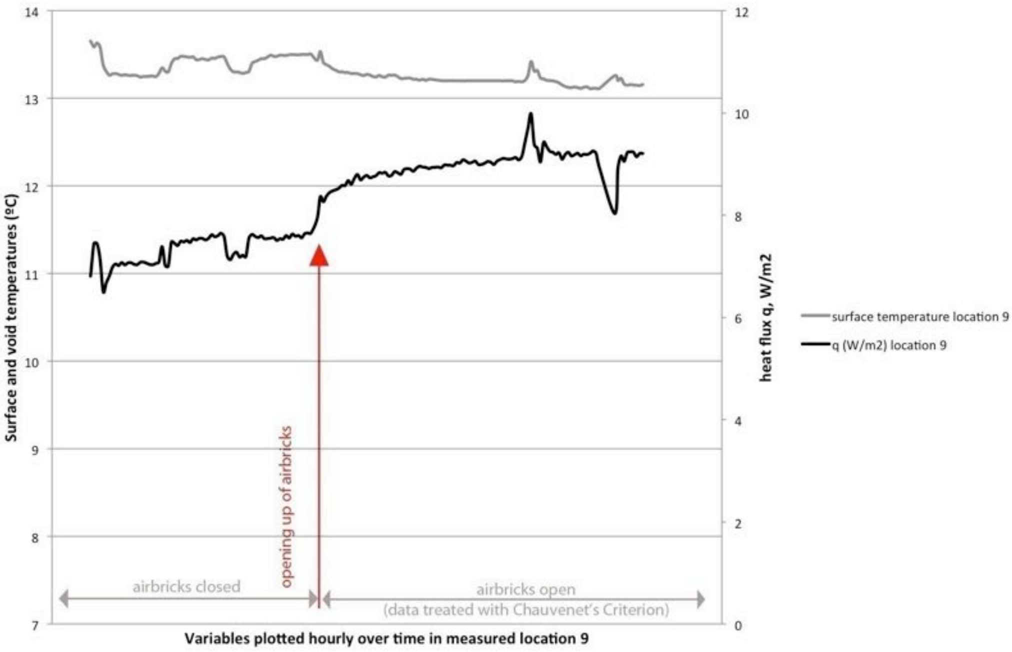

Figure 41. Location 9: hourly instantaneous heat-flux q (W/m^2; in black) and observed surface temperatures (grey, solid line) with airbricks closed and after opening up of the airbricks.

As the airbricks are located in perimeter walls, ventilative and conductive heat-transfer as a function of distance to external walls are therefore confounding variables and it is not possible to isolate the impact of these different mechanisms with airbricks open. However, with reduced ventilation in the void, for example further away from the airbricks in certain locations or with airbricks closed, this body of air below the floor surface might act as an additional thermal resistance (Harris, 1997), as discussed in Chapter 2.
Following these considerations, and given that other variables were kept the same during these observations, the closing of airbricks in this study suggested that U_p-values in the perimeter zone might have a ventilative component associated with airbrick ventilation of around 19% compared to 13% in the non-perimeter zone in these conditions.

Airbrick sealing however might lead to moisture build-up in floor voids, as discussed in Chapter 2. The implications of sealing airbricks on thermal comfort are further discussed in Chapter 6.5.

4.4.5. Impact of using air temperatures versus surface temperatures for the determination of U-values

Floor U-value models are based on the assumption that room temperatures are homogeneous throughout - see Chapter 2.3. This section illustrates that in reality room temperatures are not homogenous as also reported by Gauthier (2014)and MING XU (2001), and discusses the impact of this on U-value estimation. Inhomogeneity of room air temperatures is likely caused by a complex interplay of convective currents in the room from heating elements and from ventilation and air infiltration and from different surface temperatures.

At present it is poorly characterised where temperatures should be measured in non-homogenous spaces for the purpose of in-situ floor U-value estimation and this is further complicated by the practicalities of placing sensors, particularly in occupied houses. For walls, Siviour (1982) suggests internal air temperatures should be measured within 500mm from the sensor while Doran (2001) placed air temperature sensors 10mm away from the heat-flux sensor on the wall and a few centimetres away by BRE (2014a). No recommendations were found for floors though Thomas (1999) described temperature sensor locations approximately 12mm above the solid ground floor surface fixed on nylon wire on a timber structure. The uncertainty of temperature determination in non-homogenous spaces (as also discussed in Section 3.3), could make comparison between modelled and in-situ measured whole floor U-values more challenging.

The effect of temperature sensor height on U-value estimation was investigated in a position at the middle of the Salford EH floor (location 7, see *Figure 42.*). U-values were estimated in accordance with *Equation 48.* for air-to air U-values and *Equation 47.* where surface temperatures were used, with R_{Si} assumed to be 0.17 m^{2}KW^{-1} (BSI, 2007) and R_{Se} set to 0. Measurement uncertainties were obtained as described previously in *Equation 50.*, which reflects the natural variation of the U-value and ±5% uncertainty associated with temperature measuring locations. The observed heat-flow q and the external air temperature T_{ea} were the same in each U_p-value estimate. *Figure 42.* shows the variation of the estimated U_p-values (black data points) with temperatures measured at different heights (grey data points), ranging from 0.64 ±0.04 to 0.89 ±0.05 Wm^{-2} K^{-1} and indicates a general trend where estimated U_p-values derived from air temperatures decreased when the height of the measured air temperature in the room increased, corresponding to the observed temperature gradient.

The un-adjusted surface-to-air U_p-value (0.88 ±0.05 $Wm^{-2}K^{-1}$) was similar to the estimated U_p-value with air temperatures measured at 100mm height, i.e. 0.89 ±0.05 $Wm^{-2} K^{-1}$. However, *Figure 42.* also highlights the impact of the surface resistance on the estimated U_p-value: including the standard surface resistance of 0.17 $Wm^{-2}K^{-1}$ lead to a relative change of −14% in estimated U-value from 0.88 ±0.05 $Wm^{-2}K^{-1}$ to 0.77 ±0.04 $Wm^{-2}K^{-1}$, which was similar to the 600mm air-to air U-value estimate of 0.79 ±0.04 $Wm^{-2}K^{-1}$. If assuming that the 600mm air temperature is a proxy for ambient temperature, a surface boundary layer thermal resistance (R_{Si}) of 0.15 m^2KW^{-1} was estimated in location 7,[12] slightly below the assumed R_{Si} of 0.17 m^2KW^{-1}. Further research is required whether (a.) the 600mm air temperature is an appropriate proxy for room ambient temperature and (b.) whether this is also the case for other locations on the floor, especially closer to the perimeter where there might be less laminar flow and possibly reduced boundary layer thickness. Additionally, it is unknown what the thermal resistance of the actual boundary layers are in occupied dwellings, where the air is constantly disturbed.

While it isn't possible to identify the true heat-flow paths from these measurements, these results do highlight the potential impact of temperature sensor location on U-value estimation, though some values are within the margins of measurement uncertainty.

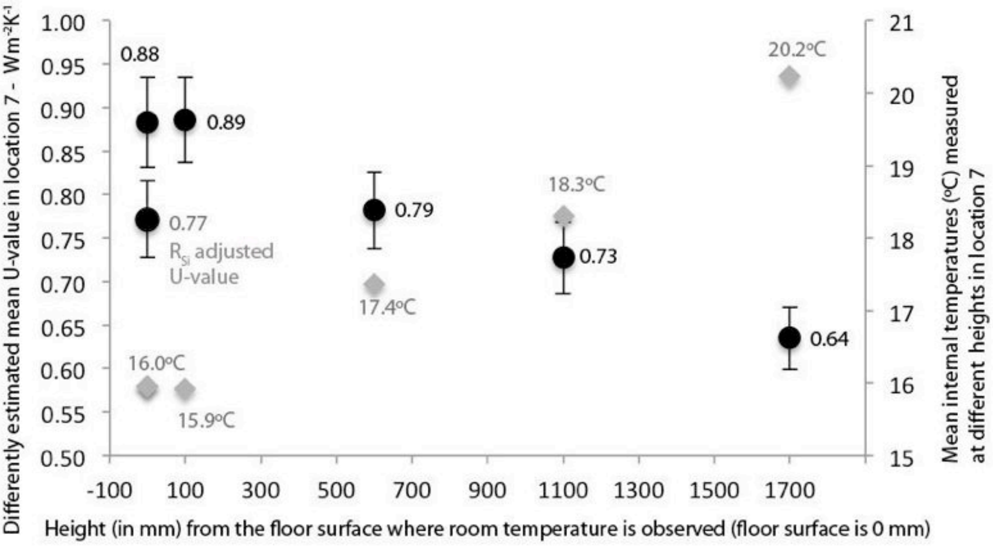

Figure 42. Estimated in-situ U-values in location 7 (middle of the floor) at the Salford EH, with differently estimated U-values (black data points) when derived with different internal temperatures (grey data points) at different heights in the room (x-axis). Error margins are in accordance with Equation 50.

[12] Simplified calculation: $R_{Si}= (T_{air}-T_{surface})/q$

Buoyancy effects tend to increase internal room temperatures as the height from the floor increases: temperatures at 100mm height were 2.4°C to 4.3°C lower than those observed at 1100mm and 1700mm height respectively[13] in the Salford EH study. In general, using higher measured temperatures increased the apparent internal-external temperature difference (*ΔT*), resulting in lower U-value estimates. However, U-values estimated from temperatures measured at the surface - before adjustment- and at just 100mm height do not appear significantly different; though diverge once the former is adjusted with the surface resistance. This is contrary to observations by Stinson (2012) who did not find significant differences in U-value when low-level skirting air temperature was used (2.5± 0.3$Wm^{-2}K^{-1}$, analysed in accordance with *Equation 48.*), compared to the U-value derived from internal surface temperatures (2.4± 0.2 $Wm^{-2}K^{-1}$, analysed in accordance with *Equation 47.* with R_{Si} adjustment). It is unknown which space heating method was used in this study; it is expected that heating method might influence U-value estimation. For instance in co-heating tests, space heating is usually provided by electrical fan heaters and circulation fans are used to mix the internal air (Wingfield, 2010b) to create less of a vertical temperature gradient. However such heating method is not representative of occupied spaces and is likely to change the heat-flow paths being measured.

The surface resistance adjustment used in surface-to-air U-value estimations assumes constant radiation and laminar (non turbulent) airflow across a sealed building element, but for example in reality external surface thermal resistances are likely to change with changing wind-speeds (see Chapter 3). Studies reported stack airflow through gaps and cracks of floors into the internal spaces (see discussion Chapter 2.2); such infiltration through gaps between floorboards is likely to disrupt the laminar flow, changing the effective surface resistance of the floor, in addition to contributing to mass-transfer heat-flow. However the impact of stack airflow on heat-transfer and floor surface resistances is unknown and difficult to characterise. It might be argued that a variable surface resistance (in different floors and for different locations on the floor) might be more appropriate than a constant value, depending on air infiltration through the floor, but this may be difficult to define and apply. Any overestimation of this surface thermal resistance would lead to underestimated U-values when U-values are adjusted for with R_{Si}. As illustrated, the significant differences in suspended timber ground floor U-values estimated via methods with and without the inclusion of a large surface thermal resistance, and possible variations in the actual surface resistances, could lead to the inaccurate estimation of U-values.

[13] This also has associated thermal comfort implications as discussed in Chapter 2.5.

This also makes comparison of estimated U-values between models and in-situ measured sources as well as between different sources which use different methods with different floor characteristics (e.g. different floor infiltration rates) more challenging. As variation in surface resistances can impact on estimated U-values, a better understanding of this factor, and how it is affected by different floor system variables, would enhance estimation of in-situ floor U-values. Additionally, there is also an uncertainty associated with characterising in-situ heat-flow via internal air temperature measurements in non-homogenous spaces, however further study of both these issues is beyond the scope of this PhD study.

On the basis of this work, estimating U-values from surface temperature to external air temperature with R_{Si} adjustment was considered preferable for the following reasons:

- Regardless of where temperatures are measured, all of the obtained U-values are 'valid' U-values though not necessarily all are representative of the heat-flow path through floors, which remains undefined at present. Measuring closer to the floor's surface might be more representative of the floor's heat-flow path compared to high up in the room and further away from the floor surface. However measuring on the floor surface requires adjustment with R_{Si}, with associated uncertainties.
- Having undertaken different temperature measurements, it is more practical and convenient to monitor surface temperatures than internal air temperatures; air temperature sensors need to be suspended from the ceiling or tripods which is not practical in the middle of the room and disruptive in occupied dwellings. Suspended temperature sensors are prone to sagging/falling of or more exposed to occupant/researcher influence while in the room.
- The use of floor surface temperatures might be more replicable as the floor surface is clearly defined.

Given the uncertainty around temperature measurements, for the purpose of this PhD and its U-value estimates, the ISO-9869 estimated ±5% air temperature error was therefore included in all U-value estimates and comparisons, including where surface temperatures were used (when this should not apply according to the ISO-9869 standard). This is to reflect some uncertainty arising from the addition of the surface thermal resistance and its impact on the estimation of U-values. It is however acknowledged that the actual effect could be much greater or smaller than the ±5% error allowed for; further research would be required to investigate this.

4.5. Insights for in-situ heat loss measurements in the field

Reflecting on both the 2012 low-resolution study and the Salford EH high-resolution study supported the understanding, development and refinement of further in-situ floor U-value measurement and analysis methods and techniques. Insights useful for future in-situ U-value measuring studies are listed below:

- Estimation of U-values from surface temperatures to external air temperatures were considered most practical. Air temperature measurements for some point locations would still be desirable to understand room temperature stratification to compare against thermal comfort theory and to compare U-values estimated with different temperatures.
- The use of an infrared camera was helpful to enable identification of areas with differing surface temperature patterns prior to placing sensors to help representative and/or purposive selection of point locations on the floor and to aid with whole floor U-value estimation at the analysis stage.
- Use of thermostatically controlled electrical heaters was useful to achieve near-constant internal temperatures in unoccupied dwellings and to avoid influence from uninsulated radiator pipes in the void. This could also allow isolation of electrical space heating energy use in the field.
- In terms of data analysis, the ISO-9869 tests were found useful as initial checks during the monitoring campaign to determine the duration of the monitoring period and to determine data inclusion for analysis. Data analysis was undertaken from U-values which met the ISO test criteria, as described in Chapter 3.3.1. However, instead of using the ISO-9869 'Average Method' for U-value estimation and error analysis, it was found more useful to treat the data statistically, by determining the mean U-value and standard deviation between daily or hourly U-values as an estimate of natural variability of the U-values, combined with ISO-9869 estimated instrument and measurement uncertainties - all as described in Chapter 3.3.4.3.
- Careful consideration is required about conducting measurements with airbricks open and with airbricks closed as this affects thermal mass equilibrium of the ground and void surfaces; additional data collection as described below might help isolate and understand such phenomena better. (This also applies to measuring in and across different seasons, addition of insulation etc.)

- It might be of interest to monitor additional variables such as void airflow, ground and void temperatures and ground heat-fluxes to obtain information about ground behaviour. Ideally they are monitored over different seasons to understand confounding variables and how they affect the rate of heat-flow (or are affected by it).
- Possible influences from lateral heat-flow and stack ventilation through gaps and cracks in the floor might affect the estimated U-values. However its impact on environmental conditions, surface resistances and instrumentation is not well characterised and was not investigated in this study and beyond the scope of this PhD research, while acknowledging that this could influence estimation of in-situ U-values.
- High resolution heat-flow measurements are anticipated to lead to decreased uncertainty in whole floor U-value estimations and might allow for comparisons with modelled and published U-values and other high-resolution studies, as long as sufficient information is provided to allow for such comparisons.

Additionally, this study highlighted that few or single point U-value measurements are unlikely to be representative of the entire construction element but are representative of the location under observation. A good spread of point U-values at high-resolution in this study was aimed for to (a.) understand the spread of U_p-values across the Salford EH floor and (b.) estimate whole floor U-values to allow for comparison with models and comparison with other sources. Despite its advantages, high-resolution monitoring is challenging to undertake, because:

- in an occupied house there is a limit to sensors that can be placed practically;
- it requires access to a large number of instruments for an extended period of time;
- installing and dismantling a high-resolution set-up is significantly more time consuming with so many sensors in place; and
- the practicalities of data checking/processing and analyses of large datasets also commands increased resources.

The following chapters will build on the methodological findings and implications of this chapter for the in-situ heat-flow measurements of a field study floor before and after some insulation interventions.

4.6. Discussion and summary

This study tested and refined in-situ heat-flux measuring methods and techniques for suspended ground floor systems; high resolution measurements were undertaken. In doing so, physical theory was tested, informing further the refinement of techniques, while the work also provided some novel observations about the influence of Salford EH characteristics on observed U_p-values. A summary of these findings is described below.

Using internal surface to external air temperatures, measurements in 14 locations produced a wide variation of U_p-values between 0.56 ±0.05 $Wm^{-2}K^{-1}$ and 1.18 ±0.11 $Wm^{-2}K^{-1}$, depending on location, supporting hypothesis H1 (*"There will be a large observed spread of U_p-values across the uninsulated floor").* For the Salford EH, the whole floor system in-situ estimated U-value, taking into account joist presence, was 0.81 ± 0.08 Wm^{-2} K^{-1}, and found to be higher than the current modelled U-values of 0.58 to 0.73 $Wm^{-2}K^{-1}$, depending on input assumptions and model used. This suggested a potential disparity between in-situ measured and modelled U-values, however given that the Salford EH is an environmental chamber, it is unknown whether such disparities will remain for a field study and the wider housing stock. The superseded CIBSE-1986 model appeared to overestimate the whole floor U-value compared to in-situ measured, though depending on model input assumptions, provided a closer match between modelled and in-situ measured whole floor U-values (Model 4). The CIBSE-1986 model gave greater importance to the ventilation opening area and wind-speeds; it is unclear how representative this is of actual and assumed inputs and performance but this might explain the divergence between the models.

In general, it was found that the observed floor U_p-values were greatest along the exposed perimeter, which reflected physical theory and solid ground floor research and supported hypothesis H2 (" *There will be increased perimeter U_p-values observed compared to locations further away from the external wall (i.e. the non-perimeter zone");* this perimeter effect was also found to be statistically significant. Sealing the airbricks reduced the estimated U_p-values between 10% to 24% depending on location on the floor; this was also found to be statistically significant and supported hypothesis H3 ("*There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks*"). There was a more pronounced U_p-value reduction effect along the perimeter from sealing airbricks and there was a slightly reduced spread of U_p-values across the floor.

Additionally, this study observed increased estimated U_p-values in the bay-wall compared to the gable wall; this effect was also retained after airbrick-sealing.

This might be explained by the joist direction and large joist depths which provided little clearance underneath and potentially acted as an obstruction to airflow movement through to the rest of the void. This might exacerbate increased thermal transmittance along the perimeter, while buffering other floor areas from colder chamber temperatures, leading to lower observed U_p-values elsewhere - as described in Section 4.4.2.

The study findings have implications for future research design and measuring techniques; in summary:

- Measuring in just a few point locations on the floor is problematic due to the large spread of U_p-values, especially when few U-value point measurements are used to estimate whole floor system U-values as representative of the entire floor. This makes comparison with modelled floor U-values, literature U-values or other in-situ studies challenging. The floor U-value models are for the whole floor; no individual points on the floor can be derived from the model.
- If fewer U_p-values are used to estimate the whole floor U-value, the greater the uncertainty associated with this whole floor U-value estimate. Depending where point measurements are observed, the whole floor U-value can be over-or under-estimated.
- Different point U-value to whole floor U-value estimation techniques can lead to different whole floor U-value estimates; an area weighted summation approach might be more robust than other explored averaging techniques in this study. It entails determining a representative and proportional floor area for each estimated U_p-values, aided by infrared images of the floor, and weighting each point location and its associated uncertainty accordingly.
- The location of temperature sensors for the determination of U-values can significantly affect the in-situ estimated U-values due to the observed vertical stratification in actual spaces. This in turn affects confidence in comparisons between in-situ measured studies and with modelled U-values.
- The inhomogeneity of room temperatures makes the use of air temperatures for the determination of floor U-values challenging. Internal surface temperatures were found to be more practical to measure and replicate, though might under-or over-estimate U_p-values due to the addition of a large constant surface thermal resistance (R_{Si}) for floors. This surface thermal resistance is based on laminar airflow which is unlikely to be the case in the field, especially given the upwards airflow from the floor void through floorboard gaps and cracks, which might change the surface thermal resistance.

This chapter highlighted the complexity of estimating in-situ U-values for suspended timber ground floor systems and comparing these results with models and other studies. Further research is required whether the above findings and measuring techniques remain valid in actual dwellings exposed to the external environment, which is investigated in the following Chapter. For a discussion on generalisability of case-study findings see Chapter 3.4.4.

Chapter 5: Measuring in-situ floor U-values in the field

5.1. Introduction

This chapter presents and discusses the analysis and results from an in-situ heat-flow field study undertaken during the winter of 2013-2014 in an unoccupied house in West London, England (STUDY 4A). Following on from the study at the Salford Energy House (STUDY 2), the heat-flow of an uninsulated suspended timber ground floor system was monitored at high resolution (27 locations) on a living room floor. Similarly to STUDY 2, airbricks were closed for a short duration to understand the airbrick ventilation effect on the observed thermal transmittance. The heat-flow in the same locations was also monitored during two floor insulation interventions, which is discussed separately in Chapter 6.

This chapter specifically addresses research question 2 ("*What is the in-situ measured thermal transmittance of floors and how does it compare to model predictions?*", supplementing in-situ heat-flux measurements of floors, while also testing research question 1 in the field (i.e. *"How should in-situ suspended timber ground floor U-values be estimated?"*), building and reflecting on the research methods and techniques developed in STUDY 2. Following hypotheses were tested (as described in Chapter 3.4.1.)

> **Hypothesis 1: "***There will be a large observed spread of U_p-values across the uninsulated floor."*
>
> **Hypothesis 2: "***There will be increased perimeter U_p-values observed compared to locations further away from the external wall (i.e. the non-perimeter zone)."*
>
> **Hypothesis 3: "***There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks."*

This chapter firstly introduces the field study and the research design prior to presenting and discussing the analysis and results of the field measurements. Implications for policy and retrofit-decision-making are briefly discussed prior to the chapter summary and summary discussion of findings.

The diagram below gives an overview of the study subject to this chapter's analysis and discussion, STUDY 4A, subject of this chapter, is highlighted in red.

STUDY 1 Field study London	**STUDY 2** Salford EH		**STUDY 3** Pre-post pilot Manchester		**STUDY 4 (A & B)** Field study Ealing				
Pilot study (2012)	**Initial study (2013)**		**Pilot study: pre-post insulation intervention study (2013)**		**Field study: pre-post insulation intervention study (2013-2014)**				
Field study, London occupied house; low-resolution monitoring: 2 locations on floor	Salford Energy House, environmental chamber; high resolution monitoring: 15 locations on floor		Manchester region, unoccupied house ; low-resolution monitoring: 4 locations on floor		West London, unoccupied house; high resolution monitoring: 27 locations on floor. Additional monitoring of environmental variables, as well as monitoring of airtightness, floor void and thermal comfort variables pre-post interventions.				
					STUDY 4 A Field study Ealing (pre-insulation)		**STUDY 4 B** Field study Ealing (post-insulation)		
Uninsulated	**Uninsulated**		**Uninsulated (pre)**	**Insulated (post)**	**Uninsulated floor (pre)**		**EPS bead insulated floor (post)**	**Woodfibre insulated floor (post)**	
Open airbricks	Sealed airbricks	Open airbricks	Open airbricks		Sealed airbricks	Open airbricks	Sealed airbricks	Open airbricks	Sealed airbricks
March 2012- April 2012	*May 2013*		*September 2013*	*October 2013*	*January 2014*		*End of January 2014-mid-February 2014*	*February-March 2014*	*mid-March 2014*
Chapter 4	**Chapter 4**		**Chapter 3 & 6/Appendix**		**Chapter 5**		**Chapter 6**		

Table 23. Summary table highlighting the subject of this chapter in red.

5.2. Field study: Research design (Study 4A)

A field study was undertaken during the winter of 2013/2014 in a 1910-built terraced house located in a London conservation area. This section describes the case study house, the research design and hypothesis testing and summarises error propagation and analysis techniques.

5.2.1. Case study description

The selected case study was a 1910-built solid walled, 2 bedroom terraced house located in the Brentham Estate conservation area in west London and was unoccupied during the duration of the study (see *Figure 43.*). Its front facade was west-facing, with 5 degrees towards south. The house had a similar ground floor area as the Salford EH but a smaller *P/A* ratio of 0.33m/m^2 due to its terraced nature and is similar to literature assumed *P/A* of 0.30m/m^2 (see Chapter 2). The 12.15m^2 living room floor (44% of the total ground floor area), had bare floorboards while the 11m^2 kitchen area was finished with 10mm block flooring on top of chipboard and the original floorboards; no access to the kitchen floor void could be obtained. On average the living room floor void was 250mm deep below the 100mm joists and was divided in 4 void sections by 3 sleeper walls - see *Figure 44.* The floor void ground was covered in dust, rubble and wood shavings and had 100 to 150mm concrete oversite, ascertained from a site survey by drilling into the ground.

The house had 3 exposed airbricks in the west-facing front facade where the living room was located, about 270 mm from the external ground - see *Figure 43.c*. Airbricks were located in between the joist depths, with one airbrick protected by a tall and wide partywall hedge. There were 2 airbricks at the back facade, which were partially protected by an open, but covered, glass greenhouse lean-to structure - see *Figure 43.b*. These airbricks sat directly above the concreted external ground and also had services in front of them, limiting the clear ventilation area. Total (free) ventilation area of all of the airbricks was estimated at 0.022 m^2.

Figure 43. a, b, c, d : The Brentham case study house: front facade (a), back facade with glass lean-to (b, lower left image), two of three front-facade airbricks (c.) (the weeds died off over winter and were maintained low during the monitoring study), one of the back facade airbricks with services in front (d.)

Case study characteristics are listed in *Table 24.;* in following sections, case-study sampling, the adopted heating strategy and instrumentation are presented.

	Case study characteristics based on site survey or as otherwise stated
Perimeter (*P*)	9.1m (breadth (b)= 4.55; length 6.1m)
Total Floor area (*A*)	27.7 m^2
P/A	0.33 m/m^2
B' = A/0.5P	6.09 m
Airbrick ventilation opening area	0.022 m^2
Total ventilation opening area per metre exposed perimeter	0.0024 m^2/m
Joist dimensions	0.050 m x 0.100 m
Joist spacing (centre to centre)	~ 0.35-0.39 m c/c
% Joist vs floor board	12%
Floor board thickness (19mm)	0.019 m
Softwood conductivity (*k*, joists & floorboards)	0.13 $Wm^{-1}K^{-1}$ (Anderson, 2006)
soil conductivity (λg)	100% clay assumed: 1.5 $Wm^{-1}K^{-1}$ (CIBSE, 2015), under approx. 100mm over-site concrete (conductivity unknown).
Foundation wall thickness (d_W)	0.22 m (based on single brick wide)
Thermal transmittance foundation wall U_W	1.7 $Wm^{-2}K^{-1}$ (CIBSE, 2015)
Height of floor surface above external ground level (*hf*)	On average 0.17 m (to the front 0.270m and to back 0.070 m; 0.25m average void depth below 0.1m joists)
R_{Si}	0.17 m^2KW^{-1} (CIBSE, 2015)
R_{Se}	0.04 m^2KW^{-1} (CIBSE, 2015)
average windspeed at 10 m (*v*)	Assumed to be 5m/s, based on RdSAP as top limit
Wind shield factor f_W	Suburban assumed: 0.05 (BSI, 2009b)

Table 24. Case study house characteristics from site survey and typical model assumptions. Note that the ventilation area required per exposed perimeter by Part C Building Regulations is 0.0015m^2/m; which is met and exceeded in this case.

5.2.2. Case study sampling & hypotheses testing

The case-study house was sampled purposively to enable the answering of the research questions set out in Chapter 2.9. and testing of hypotheses (Chapter 3.4.1.). Case-studies provide context-dependent knowledge and might lead to generalisability of findings (Flyvbjerg, 2006) and can highlight observed phenomena and can question pre-existing generalisations (Stake, 1995) - as also discussed in Chapter 3.4.4.

Six hypotheses based on the research questions were developed (see Table 11., Chapter 3.4.1.); the first three of which were tested in the previous chapter and for which some statistical significance was found. These hypotheses are further tested in this field study, while the remaining four hypothesis are subject of the following chapter. As mentioned in Chapter 3.4, an unoccupied house was identified as the best strategy to test these hypotheses; an unoccupied case-study house was purposively sampled based on the following criteria (see also Chapter 3.4.2.):

- Solid walled house with suspended timber ground floors - i.e. built pre-1919.
- Preferably a terraced house, which is the profile of over 50% of pre-1919 dwellings (Gentry, 2010), to simplify airbrick ventilation investigation.
- Unoccupied and available for minimum one winter season in 2013/14.
- Agreement from the owner to undertake disruptive and invasive monitoring, entailing the opening up of the floor to the void and later installation of insulation interventions (subject of Chapter 6).
- Near to the researcher's location to enable regular data collection and analysis and flexibility in research design adaptations.

Potential case-studies were identified from the author's stakeholder network and social media contacts, leading to two possible case-studies meeting the above criteria; the west London located case-study was favoured over a Birmingham located case-study due to travel distances; insufficient resources were available to undertake two field studies. For research ethics see Section 3.4.3.

Research management

Several research management and ethical considerations were taken into account for this field study (and the intervention study described in Chapter 6) and include risk assessments, instrument and third party insurance, informed consents and agreements about accessing the property and minimising disruption to neighbours. See *Appendix 5.A.*

5.2.3. Instrumentation

5.2.3.1. Heat-flux sensors and other instruments

As illustrated on *Figure 44.* , in-situ heat-flux sensors were placed in 27 locations on the living room floor, 18 of which were in line with the three airbricks below and 8 sensor locations offset from airbrick locations; only one location was measured on a joist. All of the sensors were attempted to be fixed in accordance with a grid, aligning sensors in both directions. However, some grid location offsets occurred due to contact errors caused by uneven floorboards or presence of nails or staples; a nearest suitable sensor location was then sought instead. Nail locations also limited sensor placement on joists. For sensor fixing details, see *Table 25.;* for instrument error see Section 5.2.4. and Chapter 3.3.4.3.

Joists were supported by three sleeper walls, dividing the void in four sections (marked by S1, S2, S3 and S4 in light-grey in *Figure 44.,* while sleeper walls are shaded in grey. The space between the joists was always clear, allowing free airflow movement between floor sections - see *Figure 46.a.* The void foundation wall between living room and hallway had no interconnected openings, though the foundation wall between the living and kitchen floor void had some limited openings. In this wall, all openings were blocked with tightly packed bubble wrap and newspaper to isolate the living room floor void from the kitchen void - see *Figure 46.b.* The reason for doing so was because the kitchen floor void had to be isolated from the living-room floor void for later floor intervention studies taking place in the living room floor only - as described in Chapter 6. Floor voids were not connected to the neighbouring houses, however there is no knowledge of the heating pattern or condition of those houses and how this may have affected the field study.

External air temperatures at the front and back of the house were monitored below the first floor window height. Heat-flux sensors on the floor were monitored with nearby floor surface temperature sensors, while air temperatures were monitored in the middle of the room at different heights (100mm, 600mm, 1100mm, 1700mm) in accordance with BS-7726 (BSI, 2002) to understand air temperature stratification and implications for thermal comfort theory and U-value determination - see Chapter 6.5. and Section 5.3.3. respectively. Void air temperatures and RH were also monitored to understand floor void conditions - see Chapter 5.3.7.3.

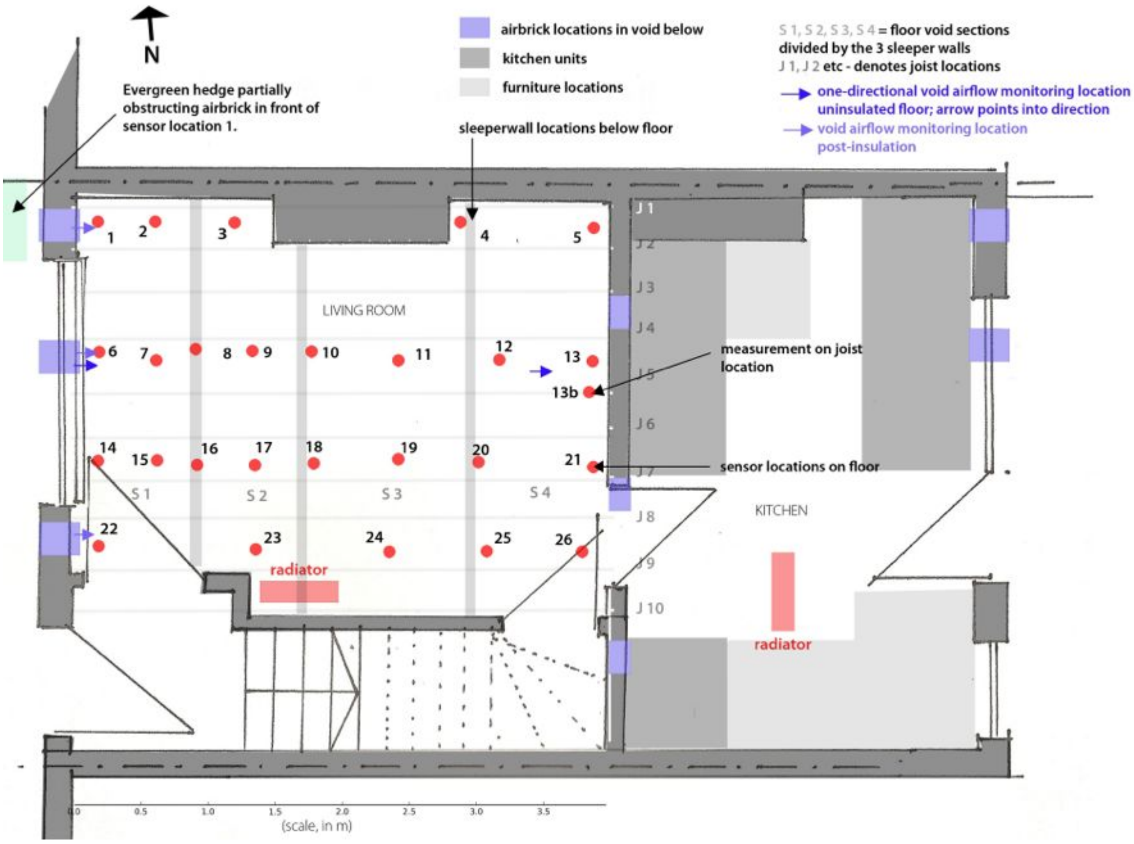

Figure 44. Case study floor plan with heat-flux sensor locations (marked in red); airbrick locations (blue); and sleeper walls (grey). Approximate joist locations are marked with a faint grey line and annotated with J1, J2 etc. Locations 1 to 5 are in line with the partially sheltered airbrick though locations 4 and 5 are located further away, behind the chimney. Locations 6 to 13 are located in line with the central airbrick, representing one of two higher resolution monitoring grids; the second higher-resolution grid includes sensors in locations 14 to 21, which are not located in line with an airbrick. Locations 22 to 26 are located in line with another exposed airbrick, while location 13b is the only location measured on a joist. Portable electrical radiators are marked in red. Figure 45.a. and b. illustrate sensors in-situ.

Figure 45.a. illustrates the instrument set up on the bare floorboard surface, which remained similar after interventions. The tripod held the internal air temperature sensors at different heights in the middle of the room.

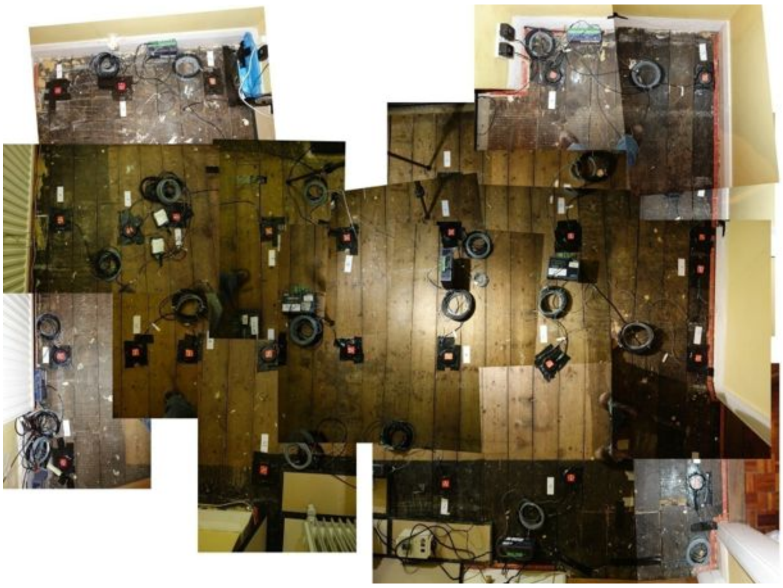

Figure 45.b. (above) illustrates the instrument set up on the bare floorboard surface, which remained similar after interventions.

Figure 46.a and b. Photographs of typical sleeper wall (left, a) and sealing of the openings in the foundation wall between living area and the kitchen area void with bubble wrap and newspaper to isolate the living room floor void from the kitchen void for later floor intervention studies taking place in the living room (see Chapter 6).

To qualitatively assess changing environmental conditions between interventions, void airflow was monitored in front of the central airbrick and at the back of the void (Section 4). At the back of the house, vertical solar radiation below the first floor window height and external windspeed at 2.8 metres above the ground were also monitored. Direct solar gain on instruments was minimised by closing a white reflective window blind at all times. The measured variables are listed in *Table 25.* alongside instrument details and fixing methods where applicable. All measurements were taken at 5 minute sequential intervals and for U-value estimation were analysed at daily intervals as also discussed in Chapter 3.3.4.3. and Section 5.2.4.

Instruments *(Associated variables/units in brackets)*	**Specification and field notes**
Heat-flux sensors (q, mV)	Hukseflux HFP01 with ±5% accuracy; the active sensing part, was kept free from any tape or instruments. Notes: sensor placement confirmed with infrared images and fixed with a thin layer of servisol heat-sink compound (thermal conductivity = 0.9 $Wm^{-1}K^{-1}$, (Farnell, 2014)) and black* duct tape along the edges and the first 100 mm of the lead. Sensors were connected to Eltek Remote Sensor GENII data loggers or Squirrel 451L or 851L data loggers and were downloaded at regular intervals to avoid data-loss. The 451L loggers were borrowed from EST, some of which failed during the monitoring period for unknown reasons, leading to some data loss in locations 17 and 18. To investigate direction of heat-flow in the void, three heat-fluxes were placed on the over site concrete (buried in the rubble and dust) in the void; two under location 22 near the external perimeter and airbrick and one under location 4; use of HFP01 in ground conditions can have accuracies of ±15%, hence two HFP01 outputs are ideally paired and averaged (Bos, 2012). * Tape colour availability limited matching floor board colour; closest match used.
Surface temperatures (T_{Si}, ºC)	Eltek thermistors with ±0.1ºC accuracy; located next to the heat-flux sensors; notes as above.
Internal air temperatures (T_{ea}, ºC)	Measured at different heights (100mm, 600mm, 1100mm, 1700mm in accordance with BS-7726 (BSI, 2002)) in the middle of the room with Eltek thermistors (±0.1ºC) connected to Eltek Remote sensor.
External air temperatures & ground temperatures (T_{ea}, ºC)	Measured at the back and front of the house below the first floor window heights with Stephenson screen shielded; Eltek Remote sensor GENII (±0.4°C). Front-of house external air temperatures were used for living room floor U-value determination. Ground temperatures were measured 1000 mm away at the front of the house, and at 300mm depth.
Floor void air temperatures (T, ºC) and relative humidity (%, RH)	Measured with Eltek Remote sensor GENII (±0.4°C, ±4% RH, up to 100% RH) in line with the central airbrick, in the middle of void section 1, 2 and 4, which enabled the checking of void conditions without lifting of floorboards. Sensors were located in open plastic boxes on the void ground.
Void Airflow (m/s)	Sontay Single-point Air Velocity Sensor AV-DSP set 0-4 m/s with accuracy of ±3% of the range, or ±0.12m/s; continuously measured and averaged over 5 minutes. Notes: Measured in front of the central airbrick in the void, both at high and low level (see *Figure 47. b and c.)* and also in void section 4 at high and low level, in line with the same central airbrick at the front of the void. Sensors were removed during bead-insulated intervention and after the woodfibre insulation the sensors had to all be placed in void section 1 and closer to the airbrick in front of lap vents, changing the sensor position pre/post insulation - see Chapter 6.4.2.2. These sensors were cowled one-directional sensors, facing the expected airflow (i.e. coming from the airbricks) - for limitations, see Section 5.3.2.5.
Wind-speed (v, m/s)	Measured with A100R Vector Instrument at 2.8 m above the ground at the back of the house to avoid theft risk; however due to its location, the windspeed may not reflect wind-speeds at the front of the house where airbrick airflow exposure was monitored in the void. Minimum wind-speed threshold is 0.2m/s; accuracy: 0.1m/s for 0.3 to 10m/s (Vector_Instruments, n.d.).
Solar radiation (W/m^2)	Averaged over 5 minutes, measured at the front of the house facing west below the first floor window; measured with CMP3 by Kipp & Zonen; uncertainty <10% of daily total (Kipp&Zonen, n.d.).

Table 25. Instrument specification and brief field notes.

Figure 47. a, b , c,: Shows the location of the external wind-speed sensor at a height of 2.8m above the ground (a) and low-level and high-level airflow sensors in the void (b) and high-level airflow sensor in front of the airbrick in location 6 (c.)

5.2.3.2. Floor void field data collection and evaluation methods

Floor void conditions (air temperature and relative humidity (RH)) were monitored in the field study house with Eltek Remote sensors (GENII, ±0.4°C; ±2% RH) which were located at the bottom of the floor void between the central joists: one sensor near the perimeter (void section 1) and two sensors further away from the perimeter (void sections 2 and 4). Data collection was constrained by access to the floor void; void access was possible through one loose floorboard per floor section to retrieve sensors at the end of the monitoring period. However this lead to the confinement of data collection and visual and physical floor data inspection to a small area of a large floor void.

The floor was also monitored with sealed airbricks; though this was for periods of < 1 week. Data was collected every 5 minutes and averaged over an hour for void analysis. Pasanen (2001) stressed the need for longitudinal measurements of temperature and RH to assess floor void conditions, as noted in Chapter 2.7. However, a significant limitation of this work was that in all cases, the monitoring periods were of short duration due to the seasonal constraints of floor heat-flow measurements and agreed access to the property. As discussed in Chapter 2.7., there is a lack of literature and models which describe a suspended floor void's hygrothermal conditions and associated mould growth risks.

The evaluation of the floor void was hence limited in this study to a brief comparison of the monitored void conditions with general literature of mould growth risk thresholds. Clearly more research and development of floor-void specific data and models are required in this area.

5.2.3.3. Heating strategy

To monitor heat-flow, a sufficient temperature difference between inside and outside is required - see Chapter 3.3. While continuous, quasi-steady-state heating (i.e. 24 hrs per day) would maximise the ΔT at all times of the day, this would not reflect actual heating nor heat-flow patterns in occupied houses (where heated and unheated periods occur, which affect measured heat-flow) nor was there sufficient time to undertake measurements with different heating regimes for comparison purposes. Additionally, continuous heating would have been prohibitively expensive as internal spaces were heated with radiant oil-filled electrical plug-in heaters due to the main central heating system being inoperative; this also removed the confounding influence of the presence of uninsulated central heating radiator pipes in the void. The radiator location is marked on *Figure 44.;* its location may have affected nearby heat-flow measurements (e.g. in location 23 and 24), though the extent of this is unknown.

The internal spaces were electrically and dynamically heated daily, similar to the heating patterns set out in the BREDEM model (Anderson, 2001). BREDEM is the basis for SAP models, which are used for Building Regulations compliance and to compare pre-and post retrofit efficiency savings (Huebner et al., 2014) and to enable future comparison with modelled performance. In the BREDEM model, the living area is assumed to be heated for a total of 9 hours to reach 21ºC between 7am to 9am and 4pm to 11pm during weekdays (Anderson, 2001). At weekends, the BREDEM model assumes a heating pattern of 7am to 11pm, however research by Huebner (2013) and Shipworth (2010) found that - for typical occupancy patterns - weekend and weekdays are heated similarly in English homes. The assumed BREDEM 21ºC heating demand temperature is similar to the temperatures reported by Shipworth (2010) for the heating profile of more than 300 occupied English homes, although the BREDEM 9 hour daily heating assumption is slightly above the mean heating hours of 8.2 to 8.4 during weekdays and weekends respectively for the English home sample (Shipworth et al., 2010).

As such the same BREDEM weekday heating pattern (21ºC between 7am to 9am and 4pm to 11pm) was used for weekday and also weekends for the field study living room, kitchen, and one of the upstairs bedrooms.[1] The stairwell, hallway, bathroom and second bedroom remained unheated; the impact of unheated spaces on measured heat-flow is unknown. The internal doors between kitchen and living room and living room and stairwell remained closed during the duration of the study.

Given the impact of heat input on U-value estimation, it is important to capture the heat-flow over 24 hour intervals and to take care that no bias is created by removing outliers.

5.2.3.4. Sealing airbricks

For the monitoring of heat-flow with reduced floor void ventilation, the sealing of airbricks was done two-ways to the front of the house:

1. **from the outside** by placing weather-proof obstructions in front of the airbricks, after taping over the metal airbrick surface - See *Figure 48. a. and b.*
2. **from the inside** by pushing newspaper and bubble wrap into the airbrick space - See *Figure 48. c.*

For the back facade, the airbricks were protected from rain at the back of the house by the glass lean-to structure and the airbricks were simply taped from the outside - see *Figure 49*.

Figure 48.a., b., c.: sealing of front facade airbricks; clockwise from left to right: external taping over the metal airbrick (a); covered with boxes filled with weights (b) and sealing from the inside with bubble wrap (c)

[1] For kitchens and bedrooms, BREDEM assumes an 18ºC heating demand temperature where rooms are separately controlled and assumes reduced heating hours. Where there is no separate zoning, the assumption is that the same heating times apply in non-living spaces, as was assumed in the field study. Contrary to BREDEM however, demand temperatures of 21ºC were used in the kitchen and bedroom; this was done to enable another in-situ heat-flux study to take place in the bedroom (i.e. to create sufficient ΔT) and to minimise influence from a colder kitchen area (including the kitchen floor void) on the living room floor void.

Figure 49.a., b.: Sealing of back facade airbricks by taping over the metal surface.

5.2.3.5. Field study limitations

The main field study limitations and issues are identified below; all of which require future research.

- **Limited calibration checks:** All the temperature sensors were checked 'side by side' in both a cold and warm UCL chamber while some other experiments were taking place in the thermal lab. All temperature and RH sensors measured within their stated instrument accuracy under the lab conditions (~10ºC in cold chamber and ~20ºC in the warm chamber), which are similar conditions to those encountered in the internal room or floor void conditions - see Chapter 6.5.and Section 5.3.7. However no calibration checks (as described in Chapter 3.3.5.) were undertaken for the heat-flux sensors: there were no suitable wall surfaces available in the thermal lab due to other studies taking place.

- **The whole floor U-value is derived from living room floor only**: the whole floor U-value is derived from the living room floor only, which represents 44% of the entire ground floor. It is assumed that similar heat-transfer applied across the rest of the floor, creating uncertainty around the whole floor estimated U-value. The impact of unheated spaces on measured living-room floor heat-flow is unknown.

- **Only one joist location measured:** due to joist locations having nail or holes in boards, measuring joist heat-flux is limited to suitable locations where surface contact is sufficient. The lack of several measured joist locations and the exclusion of a perimeter joist location measurement is a limitation of this field study (and likely future field studies). Implications of this for whole floor U-value estimation are discussed in Section 5.3.2.

- **Missing data:** the study started late due to electrical supply failure to the external temperature data logger and to the electrical heater in the living room (due to an electrical fault with the kWh readers). Some data loggers failed, leading to missing data of a few days (in between site visits) in sensor locations 17 and 18 and a few hours for locations 6 to 9. The late start of the study meant that the uninsulated floor study with sealed airbricks had to be cut short to 4 days, leading to less robust results - see Section 5.3.7.

- **Sealing of airbricks:** In the field study, airbricks in the living room were taped both from the outside as well as sealed with bubble wrap from the inside; but the foundation walls might not be airtight so that closing of airbricks on its own may have no or limited effect on heat loss as observed by Hill (2005).

- **Measuring void airflow:** void airflow was measured with one-directional sensors - see Section 5.2.3. In front of the airbricks, the airflow direction is more likely to be in the direction of the sensor; however, other patterns of air movement and from different directions were excluded.

- **Exclusion of uninsulated, heated central heating pipes in the floor void:** radiator heating pipes typically run through floor voids (often in localised areas) and condition the void and floor surfaces. This is expected to significantly affect observed heat-flow (and possibly thermal comfort thresholds). This study was undertaken without the effect of heated radiator pipes in the void; and this is also excluded in floor U-value models. While this would have added complexity to the study, the effect of heat-flow from radiator pipes is outside the scope of this research. The spaces were electrically heated and given the non-functioning central heating-system in the case-study, no comparative study could be undertaken and this has been noted for future research.

- **Short-term monitoring only of floor void conditions:** due to access arrangements, the floor void could only be monitored over a short period, hence limiting comparison with both literature and post-insulation monitored data - see Section 5.3.7.

- **Limitations with other measured variables are provided in *Appendix 5.B*.**

5.2.4. Error propagation and data analysis procedures

This section gives a brief summary reminder of the error propagation and data analysis procedures as set out in Chapter 3.3.4.3. and comparable to the techniques applied for the Salford EH, see Chapter 4.3.4.

5.2.4.1. Data analysis and measurement uncertainty

The mean U-values were estimated in accordance with *Equation 47.* , including adjustment with surface thermal resistance R_{Si} of 0.17 m^2KW^{-1} where internal surface temperatures were used; all estimates include adjustment for the thermal resistance of the heat-flux sensor itself (see Chapter 3.3.).

The measurement uncertainty for the in-situ estimated U-values is estimated from *Equation 49. (page 125)* and as repeated in *Table 26.*, where the standard deviation is a measure of the natural variability of U over the monitored period. At the Salford EH, an hourly mean and its *sd* was calculated however for the field data a clear day/night cycle exists and a daily mean and daily *sd* are estimated instead - justification for this was set out in Chapter 3.3.4.3, page 124.

Contrary to the Salford EH, the natural variability of the uninsulated floor constitutes a large component of the total uncertainty; this is caused by the changing external environmental conditions alongside a changing space-heating pattern, which is absent at the Salford EH.

To illustrate: the intrinsic instrument error and the (extrinsic) measuring condition error make up approximately ±9% of the overall error - see Chapter 3.3.4. Added to this is the natural variability component of U and in the field-study was found to be between ±4 to ±13%. In the Salford EH this was found to be ≤ ±5% (after research influence outlier removal - see Chapter 4.3.4 and 4.3.5.). For the field-study this lead to total measurement uncertainties between ±10 to ±16% depending on point location on the floor (see *Table 27.)*, while for Salford total measurement uncertainty was estimated between ±9 to ±11%.

For comparisons between open and sealed airbricks and comparisons for the same point location with different temperature data, contact, edge heat loss and instrument errors need not be included as these sensors remained in place – see *Equation 50*. (in *Table 26.)* and as discussed in Chapter 3.3.4.3.

Identified errors - see Chapter 3.3.4.	**Applicable for each point-measurement without comparison**	**Applicable for each point-measurement when comparing each intervention with airbricks open/closed or when comparing U-vales estimated with surface or air temperatures**
Intrinsic: Instrument error (calibration heat-flux and temperature sensors) ± 5%	± 5%	n/a
Extrinsic: Measuring condition error - **Edge heat-loss error**	±3%	n/a
Extrinsic: Measuring condition error - **Contact error**	±5%	n/a
Extrinsic: Measuring condition error - **Temperature location measurement error**	±5%	±5%
Natural variability U (inherent property, not a measurement error) - *sd* of daily Umean	± sd	± sd
Final estimated error	$\sqrt{5^2+3^2+5^2+5^2+sd^2}$ *Equation 49.*	$\sqrt{5^2+sd^2}$ *Equation 50.*

Table 26. Identified errors and applicability; for further detail see Chapter 3.3.4.3., page 124

5.2.4.2. Removal of outliers

After calculating U-values from hourly data, outliers were removed using the Chauvenet Criterion (for explanation of Chauvenet's Criterion see Chapter 4.3.5.); outliers caused by for example researcher influence and blower door tests (which are weather dependent and had to be carried out when possible) were removed. As described in Chapter 3.3.4.3., hourly U-values were averaged over each day to calculate the mean value of U and its standard deviation *sd* as the natural variability of U between the monitored days in each location. U-values over the monitored period were assessed by the ISO-9869 test criteria (see Chapter 3.3.1.). These tests were undertaken on raw data, without outlier removal to ensure multiples of a full 24 hours. For the uninsulated floor, all ISO tests were met for all point U-values after 12 days of data collection, though were analysed for the full 13 days of monitoring.

For the 27 sensors on the floor, between 3 and 10 hourly data points were removed by Chauvenet's Criterion, from a total of 312 hourly data points, i.e. up to 3%. The mean daily U-values obtained from raw data and from Chauvenet treated data were within 1 to 2% for each point location; generally outlier removal lead to a slightly lower U-value estimation. The *sd* as a proportion of U was reduced by between 1% and 24% - see *Appendix 5.C.*

5.3. Analysis, results and discussion

This section presents the estimated uninsulated floor system point U-values and discusses the spread of the U_p-values, followed by an estimated whole floor system U-value and comparison to literature and models.

5.3.1. Spread of point U-values and perimeter effect

Based on the aforementioned data and error analysis protocols and using internal surface to external air temperatures, estimated U_p-values ranged from 2.04 ±0.21 $Wm^{-2}K^{-1}$ above the central airbrick along the perimeter (location 6) to values a quarter of this furthest away from the perimeter (0.54 ±0.09 $Wm^{-2}K^{-1}$, location 5). All estimated point-U-values are listed in *Table 27*. The greatest U_p-values were observed in locations 6 and 22 (1.99±0.21 $Wm^{-2}K^{-1}$), near the central and third airbrick. The first airbrick (below location 1) was protected by a large hedge and might be the reason why there is still significant, but slightly reduced heat-flow in this location (1.74 ±0.18 $Wm^{-2}K^{-1}$).

As expected and as also observed in the Salford EH, the uninsulated living room floor system in the field study house had a large spread of U_p-values across the floor. In general, a clear negative association exists between the measured U_p-value in a location and its distance from the external perimeter wall. As illustrated by *Figure 50*., estimated U_p-values progressively reduce with the distance from the perimeter wall. As discussed in Chapter 4.4.1., a 1000mm perimeter zone was used for graphical representation and hypothesis testing and was also used here for the same purpose. The second hypothesis H2 ("*There will be increased perimeter U_p-values observed compared to locations further away from the external wall (i.e. the non-perimeter zone)")* was supported by an unpaired Mann-Whitney U (Wilcoxcon rank sum): Mann–Whitney W = 147, n1 = 9; n2 = 17,P < 0.05 (0.00002 or about 2 tests in 100,000, unpaired): i.e. the difference in U_p-values between the perimeter zone (locations within 1000mmm from an external wall) and the non-perimeter zone of the floor (sensor locations further away than 1000mm) was statistically significant. The estimated mean of the 9 perimeter located point U-values was 1.54 ±0.17 $Wm^{-2}K^{-1}$, 1.8 times greater than the estimated mean of the 17 point U-values located in the non-perimeter zone (0.85 ±0.11 $Wm^{-2}K^{-1}$). As also discussed in Chapter 4.4.1, the extent of the perimeter effect is less clear as there was no abrupt change after 1000mm, but instead a gradual reduction in U_p-values the further away from the external environment was observed - see *Figure 50.*

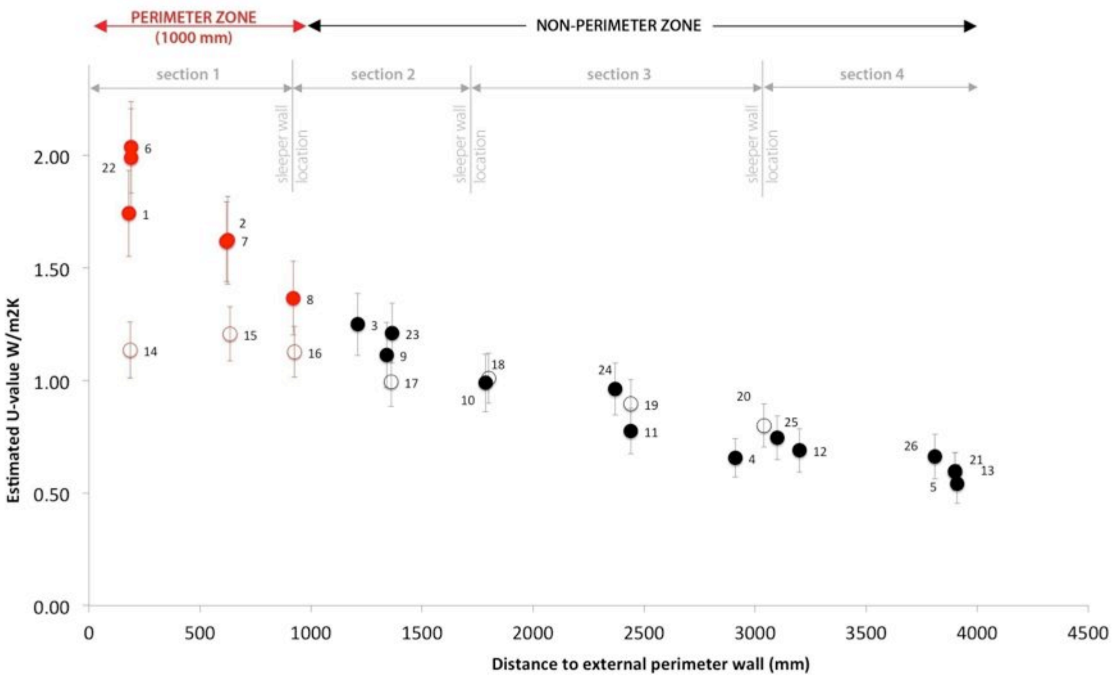

Figure 50. Presents 26 estimated point U-values on the floor (excluding joist location); the red data points were located in the 1000 mm perimeter zone (as per Chapter 4.4.1); the black data points were not located in the perimeter zone; the outlined data points are those not aligned with an airbrick; while the solid ones are aligned with airbricks. Error margins derived as per Equation 49. The three sleeper wall locations are marked up, dividing the floor void in 4 sections; see also Figure 44. It is unclear why the estimated U_p-value in location 14 near the perimeter wall was slightly lower than U_p-values in location 15 and 16 (further away from the perimeter wall), though values are within the margins of error.

For this field study, similar U_p-values (within the margins of error) were observed when sensor locations were in parallel locations, i.e. when aligned with airbricks and at similar distances away from the perimeter wall (see solid data points in *Figure 50.)*. When locations were observed in the perimeter zone but not aligned with airbricks, (locations 14 to 16, red outline data points in *Figure 50.*), point U-values were significantly lower than those in front of airbricks (red solid data points). However the effect of the airbricks and void airflow on estimated point U-values was no longer clearly visible further away from the 1000mm perimeter (solid black data points compared to outlined black data points) and beyond the first sleeper wall.[2] This might be explained by the presence of the sleeper walls in the void acting as obstructions to cross-flow movement of incoming colder external air further along in the void.

[2] The first sleeper wall was located below sensor locations 8 and 16 (with a 100 mm air gap below) at about 900mm from the external wall in the void (see *Figure 44.)*.

This observed sleeper wall obstruction effect appears comparable to the deep joists acting as airflow obstructions in the Salford EH, as discussed in Chapter 4.4.1. This is also tentatively supported by low void airflow measurements in floor void section 4 (- see also discussion in Section 5.3.7.). It should be noted that airflow measurements were undertaken with one-directional sensors, likely not capturing all airflow presence. However low airflow measurements might also be caused or exacerbated by isolation of the kitchen and living room floor voids (see Section 5.2.), assumed to reduce cross-flow.

Figure 51. supports the first hypothesis (H1) that *"There will be a large observed spread of U_p-values across the uninsulated floor"* and supports the second hypothesis of increased thermal transmittance along the perimeter; distance to the perimeter walls and airbrick locations are confounding variables as also discussed in Chapter 4.4.1. The thermal transmittance is more pronounced along the open airbricks; this is further investigated by comparing U-values with sealed airbricks - see Section 5.3.7.

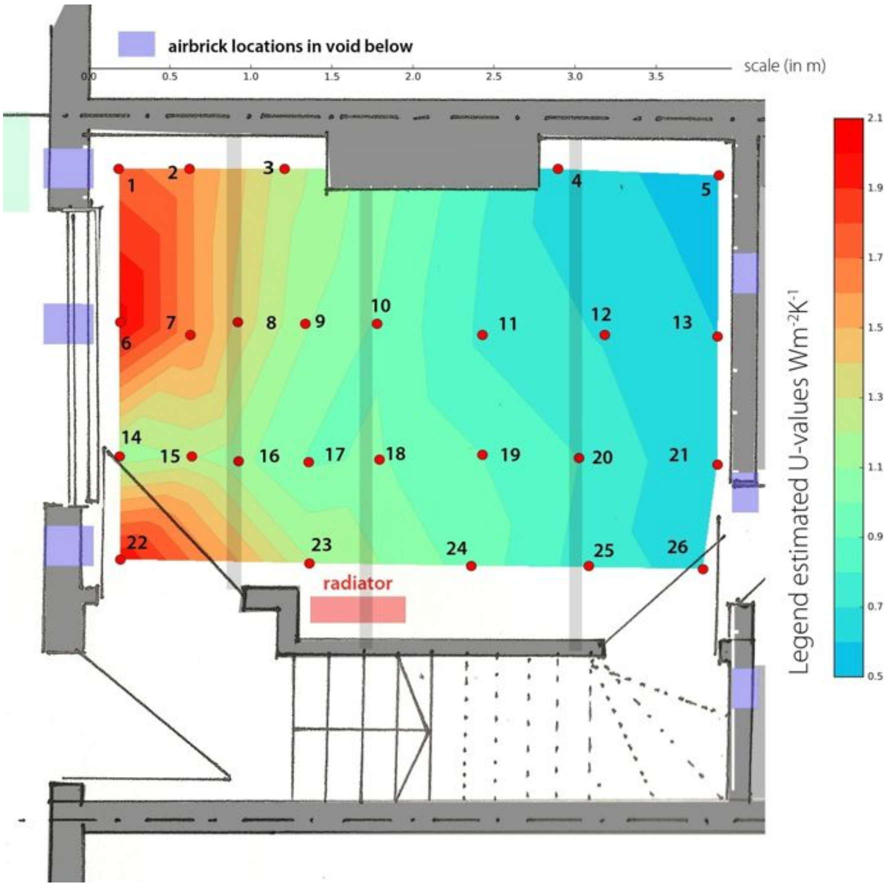

Figure 51. Presents linearly interpolated U_p-values as a heat map between observed point U-value locations for the uninsulated floor; point locations are marked with a red dot; sleeper wall locations are indicated in light grey shade. Note that the map only shows interpolated values between points, no values between the walls and the points (hence the white zone). For estimated point U-values also see Table 27. Note: joist presence not accounted for.

OPEN AIRBRICKS				
Location	**Uninsulated floor- mean U (outliers removed)** $Wm^{-2}K^{-1}$			***final error (%)***
HF1	1.74	±	0.18	*11*
HF2	1.62	±	0.18	*11*
HF3	1.25	±	0.14	*11*
HF4	0.66	±	0.09	*13*
HF5	0.54	±	0.09	*16*
HF6	2.04	±	0.21	*10*
HF7	1.62	±	0.19	*12*
HF8	1.37	±	0.16	*12*
HF9	1.11	±	0.14	*13*
HF10	0.99	±	0.13	*13*
HF11	0.78	±	0.10	*13*
HF12	0.69	±	0.09	*14*
HF13	0.60	±	0.09	*15*
HF14	1.14	±	0.12	*11*
HF15	1.21	±	0.12	*10*
HF16	1.13	±	0.11	*10*
HF17	0.99	±	0.11	*11*
HF18	1.01	±	0.11	*11*
HF19	0.90	±	0.11	*12*
HF20	0.80	±	0.09	*12*
HF21	0.60	±	0.09	*15*
HF22	1.99	±	0.21	*11*
HF23	1.21	±	0.14	*11*
HF24	0.96	±	0.11	*12*
HF25	0.75	±	0.10	*13*
HF26	0.66	±	0.10	*15*
HF_Joist(13b)	0.51	±	0.07	*14*

Table 27. Estimated point U-values for the uninsulated floor, alongside their estimated absolute and fractional uncertainties (in grey).

5.3.2. Whole floor U-value

The whole floor U-value was derived from the living room floor only which represented 44% of the entire ground floor. This created unknown uncertainty around the whole floor U-value, but it allowed for comparison with models (where the same characteristics of the living room floor were used).

As defined earlier in Chapter 4.4.2., the whole floor U-value estimation was calculated as an area-weighted summation in accordance with *Equation 52*. *Figure 52.* illustrates the 12.15 m^2 living room floor plan and a representative area grid derived from sensor locations and with support from infrared images.

The whole floor U-value was estimated as 1.04 ±0.12 $Wm^{-2}K^{-1}$.[3] As discussed in Chapter 3.3.2., uncertainty arises from representative area estimations; different area configurations were tested along the perimeter, however this did not lead to any differences past the third significant digit of the whole floor obtained U-value.

Only one joist location was measured near sensor location 13 away from the perimeter, as marked on *Figure 52*. and as discussed in Section 5.2.3. The estimated point U-value on the joist was 0.51 ±0.07 $Wm^{-2}K^{-1}$, just 15% below the point U-value of 0.60 ±0.09 $Wm^{-2}K^{-1}$ in location 13 and within the margins of error. This thermal transmittance reduction is significantly less than the 21% U-value reduction of a Salford EH joist, however this difference is likely explained by (a.) joists were 190mm in the Salford EH and just 100mm in the field study and (b.) the location specificity of observed thermal transmittance reduction; in the Salford EH, joist measurement was along the exposed perimeter: addition of an increased thermal resistance (i.e. the joist) will have a greater proportional heat-transfer reduction impact where heat-flow is higher (i.e. along the perimeter). For the reasons above and given that the difference was within the margins of error, no joist adjustments were made for the field study[4] and is a limitation of this study as noted in Section 5.2.3.5.

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[3] This was similar to but slightly below the simple whole floor U mean estimate of 1.09 ±0.13 W/m^2K.

[4] Joist adjustment would lead to a whole floor U-value of 1.02 ±0.12 $Wm^{-2}K^{-1}$, close to the unadjusted whole floor U-value.

Figure 52. illustrates the living room floor plan with each of the 26 measured locations assigned a representative area A (m²) (as technique discussed in Chapter 4.4.2.) and differentiated by different colours on the plan. Note that the colours have no meaning other then each colour distinguishes one area around a HF sensor from another; blue zones denote airbrick locations; red circles are the HF locations; grey vertical lines are floorboard locations.

Given that the Salford Energy House is a semi-detached property, it had a greater exposed perimeter (*P/A* of 0.57 m/m²) compared to the field study (*P/A*=0.33m/m²). If just taking the *P/A* into account, the Salford EH might be expected to have a larger whole floor U-value than the field study but this was not the case. Based on the living room floors in both cases, the Salford EH whole floor U-value estimate (0.81 ±0.08 $Wm^{-2}K^{-1}$, taking joists into account) was about 20% below that estimated for the field study. However, U-value comparisons between the Salford EH and the field study are difficult given that the Salford EH was not an actual house; both floor constructions and measuring conditions differed significantly, e.g. the Salford EH had lower airbrick ventilation openings compared to the field study (0.00077 m²/m versus 0.0022 m²/m) and was kept at semi-steady-state and not exposed to real conditions such as actual wind-speeds, all variables which are likely to have affected the measured heat-transfer. Further differences with actual dwellings were discussed in Chapter 4.3.1.

Comparison between point-U-value locations in the field and in the Salford EH were similar for the non-perimeter zone of the floor, but not for the perimeter zone: in Salford point U-values ranged between 0.73 and 1.18 $Wm^{-2}K^{-1}$ in the perimeter zone near airbricks, while U_p-values observed in the field study near the perimeter and airbricks ranged between 1.74 and 2.04$Wm^{-2}K^{-1}$ (locations 1, 6 and 22). Clearly these relatively low point U-values along the Salford perimeter were influential in the estimation of a lower whole floor U-value compared to the field study.

5.3.3. Impact of using air temperatures versus surface temperatures for U-value estimation

It was illustrated in Chapter 4.4.5. that different U-values were estimated for the Salford EH depending on which internal room temperatures were used to represent the ambient room temperature for estimation of U. This was associated with inhomogenous room temperatures. Similar findings were found for the field study and this is illustrated by the centre of the floor location 10 in *Figure 53.,* but within the margins of error for the field study. As in the Salford EH, internal room temperatures increased as the height from the floor increased. Hence point U-values derived from air temperatures decreased when the height of the measured air temperatures increased, corresponding to the observed temperature gradient. The estimated U-values in the field study for location 10 ranged from 0.85±0.07 $Wm^{-2}K^{-1}$ to 1.22±0.13 $Wm^{-2} K^{-1}$ depending on the height of temperature measurements and were generally within error margins - see *Figure 53.*

As in the Salford EH (see Chapter 4.4.5.), the U-value estimated from 600mm high air temperatures was similar to the R_{Si} adjusted U-value estimated from observed floor surface temperatures (red datapoint in *Figure 53.)*. Assuming the 600mm air temperature as a proxy for ambient temperatures, gave a surface boundary layer thermal resistance (R_{Si}) of 0.15 m^2KW^{-1},[5] slightly below the assumed R_{Si} of 0.17 m^2KW^{-1}; this was similar to the Salford EH but it is unknown if this remains in other floor locations[6] or studies.

[5] Simplified calculation: $R_{Si}= (T_{air}-T_{surface})/q$

[6] Air temperatures at different heights were not measured for each of the 27 heat-flux sensor floor locations, hence only comparison for location 10 could be made in this study, where such data was collected.

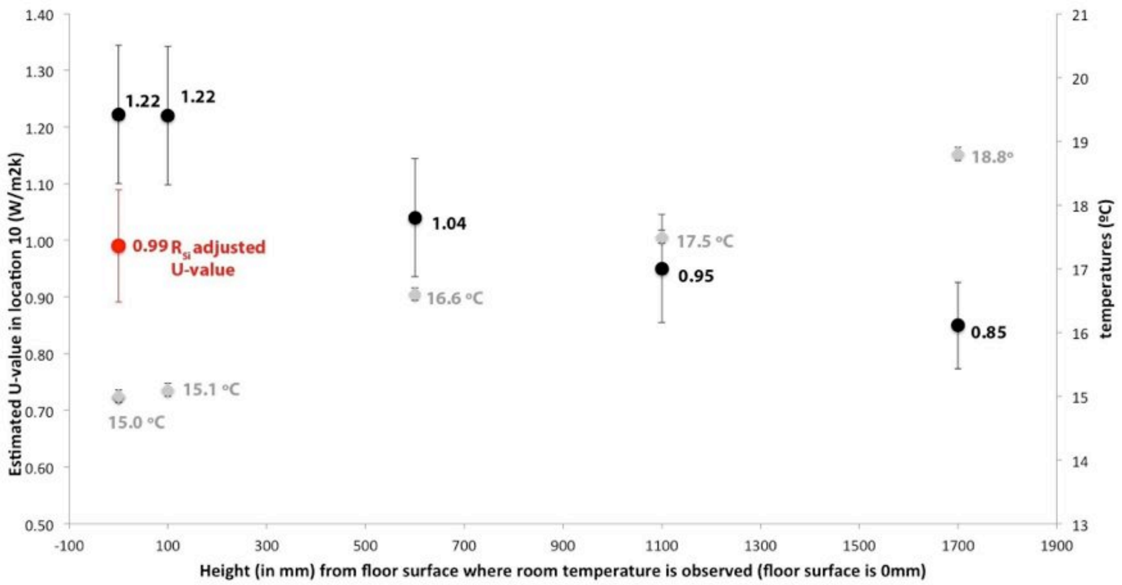


Figure 53. Estimated in-situ U-values in location 10 with differently estimated U-values (black data points) when derived with different internal temperatures (grey data points) at different heights in the room (x-axis); error margins in accordance with Equation 50. Note that the U-value derived from the middle of the floor with air temperatures measured at 600mm high (1.04±0.10Wm^{-2} K^{-1}) is similar to the whole floor U-value obtained from 26 locations on the floor using surface temperatures. Further research is required in a larger sample to investigate if similar findings apply elsewhere.

Slight differences, but also within error margins, were also observed in U-value estimations depending on where external temperatures were measured (i.e. at the front of the house or at the back of the house). External temperatures measured in a sheltered position will lead to a smaller ΔT and hence higher estimated values - while the reverse is true for more exposed external temperature sensor locations.

While within margins of measurement uncertainty, ambient temperature determination adds to uncertainty, making comparison between steady-state modelled U-values (where internal and external temperatures are stable and homogenous) and dynamic and location-specific in-situ measured U-values more challenging. This illustrates that careful research design and transparency in reporting are required, alongside the value in monitoring conditions in different locations. Further research might include additional air temperature measurements and room airflow to investigate the thermal resistance of the surface boundary layer across the floor.

5.3.4. Estimating a whole floor U-value with fewer point measurements

As discussed in Chapter 4.4.2.5., measuring in just a few point locations is highly likely to significantly over-or underestimate the whole floor U-value; this was also confirmed for the field study: 70% of values estimated by averaging just two point-measurements would under- or over-estimate the whole floor U-value - this is illustrated by *Figure 54.;* 30% of the paired U-values had overlapping error margins which fell within the error margins of the whole floor U-value. Only 21 paired U-values (or 6.5%) matched the estimated mean U-value closely (i.e. where the mean U-value overlapped with the whole floor U-value error margins, i.e. between 0.92 to 1.16 $Wm^{-2} K^{-1}$). Just 1 paired location matched the uninsulated whole floor U-value exactly (pairing of locations 9 and 24).

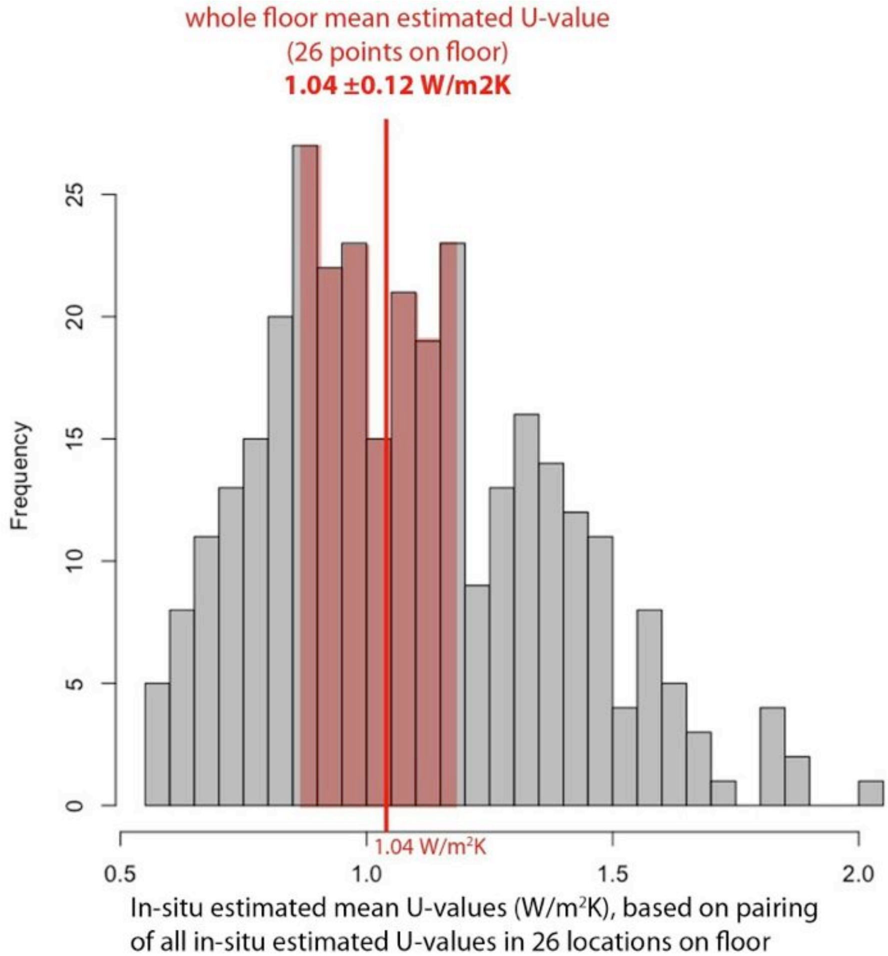


Figure 54. Histogram of the 325 paired U-values; the red line indicates the whole floor estimated U-value, while the red zone indicates the U-value distribution within the error margins of the whole floor U-value (97 pairs (or 30% of all combinations); the grey bars are mean U-values from two locations on the floor which fall outside the whole floor U-value uncertainty margins. Note no joist presence is accounted for.

In summary, only a small proportion of paired U-values gave a similar whole floor U-value as obtained from high-resolution measurements and indicated the limited use of low-resolution measurements to obtain a whole floor U-value. This is in support of the discussion in Chapter 4.4.2.5., reiterating that random selection of measuring locations is highly likely to lead to a poor representation of the whole floor U-value due to the large spread of heat-flow across the floor surface. Only by measuring at high-resolution can insights be gained of the combined sensor locations which would give a U-value estimate close to the whole floor U-value. In this field study, there is no real pattern, though locations near the airbricks and <800mm from the perimeter were generally excluded to obtain a close whole floor U-value. This is likely to differ depending on floor and dwelling characteristics - further discussion in Chapter 6.4.2.3.

5.3.5. Comparison to literature and other in-situ studies

Literature - theoretical values

The average published U-value of a terraced house was found to be 0.55 $Wm^{-2}K^{-1}$ and was between 0.45 $Wm^{-2}K^{-1}$ to 0.70 $Wm^{-2}K^{-1}$ - see Chapter 2.4.1. This is clearly significantly below and outside the margins of error of the estimated whole floor U-value of 1.04 ±0.12 $Wm^{-2}K^{-1}$ (i.e. 0.92 to 1.16 $Wm^{-2} K^{-1}$) for the field study.

Literature - in-situ reported values

The estimated in-situ U_p-values located in the perimeter zone in this field study ranged between 1.14 ±0.12 $Wm^{-2}K^{-1}$ (location 14) and 2.04 ±0.21 $Wm^{-2}K^{-1}$(location 6) and are similar (though slightly below) the perimeter point U-values of 1.19 $Wm^{-2}K^{-1}$and 2.4 $Wm^{-2}K^{-1}$ as reported by others (see Chapter 2.4.2.). Given that the latter in-situ point floor measurements are from different housing typologies and were generally single spot measurements in specific locations, comparison between these in-situ reported measurements and U_p-values as well as the whole floor U-value obtained from 26 point locations across the floor in this field study is uncertain and challenging.

5.3.6. Comparison to modelled U-values

The modelled floor U-value was estimated using the ISO-13370 model as described in Chapter 2.3 and with CIBSE-2015 and RdSAP and the superseded CIBSE-1986 model. Where available, input data was adapted after the site survey to calibrate model inputs to increase the accuracy of the model (as recommended by Park (2013) and Lee (2013)). Inputs which could not be obtained from a survey were assumed based on typical assumptions - as listed in *Table 24.* Measured external wind-speeds were excluded in the model as they were taken at 2.8m instead of the 10m assumed in the model. The models were based on living room area characteristics to allow for comparison to the in-situ estimated whole floor U-value, limitations of doing so were noted in Section 5.2.3.5.

U-values were modelled with and without joist presence, but this made no significant difference to the resulting U-values (see *Table 28.)*; joists were excluded in the in-situ measurements as discussed in Section 5.3.2. Depending on which current model is used, the whole floor U-value was estimated between 0.51 and 0.57 $Wm^{-2} K^{-1}$, as set out in *Table 28.* These modelled values are within the ranges of published U-values for terraced houses of 0.45 to 0.70$Wm^{-2} K^{-1}$(see Section 5.3.5.), but significantly below this field study's in-situ measured whole floor U-value of 1.04 ±0.12 $Wm^{-2} K^{-1}$. The in-situ estimated whole floor U-value was about twice as high than the current U-value model estimates and outside the margins of in-situ measurement uncertainty; > 20% disparity is considered significant by ISO-9869 (BSI, 2014).

The superseded CIBSE-1986 model estimated significantly higher floor U-values than the current models, providing an estimate nearly 30% higher than the whole floor estimated U-value. Possible reasons for the disparity between the old CIBSE-1986 and current floor U-value models were discussed in Chapter 4.4.3 and included greater influence by the CIBSE-1986 model of ventilation opening area and assumed wind-speeds. Changing wind-speed from 5m/s (as suggested by RdSAP) to 1m/s (as recommended by the CIBSE-1986 model - Chapter 2.3.1.) lead to the (current) model outputs diverging even further from the in-situ measured whole floor U-value, whereas the CIBSE-1986 model reduced to 1.04 $Wm^{-2} K^{-1}$, aligning with the in-situ estimated whole floor U-value for this field study.

It is however unclear whether this is due to the combination of assumed model input variables for this field study or due to the ability of the CIBSE-1986 model to capture floor thermal transmittance more accurately. A larger sample of high-resolution in-situ floor heat-flux measurements of a variety of floors are needed to investigate model accuracy and test whether the CIBSE-1986 model outputs are a better predictor of actual floor thermal transmittance compared to the current models.

Input assumptions (as per *Table 24.*) unless stated otherwise; *(assumed 1m/s wind-speed in brackets)*	**Output ISO-13370**	**Output RdSAP**	**Output CIBSE**	**Output CIBSE 1986** *(assumed 1m/s wind-speed in brackets)*[7]
All models based on survey input assumptions; U-value out puts, $Wm^{-2} K^{-1}$				
Uninsulated floor, excluding joist presence	0.57 *(0.51)*	0.51 *(0.46)*	0.52 *(0.45)*	1.34 *(1.04)*
Uninsulated floor, including 12% joist presence	0.57	0.51	0.51	1.31 *(1.03)*

Table 28. Whole floor modelled outputs for the field study ; joists where excluded to allow comparison with the whole floor in-situ estimated U-value.

Differences between models and in-situ results provide an opportunity to understand more deeply both modelling and in-situ approaches and improve both. Possible reasons for this disparity might be because models are based on simplified assumptions about certain variables (such as wind-speed, wind-shielding factors, material and ground conductivity - see Chapter 2.3.). For instance, it has been previously noted that wrongful assumptions about ground conductivity can lead to significantly differently estimated U-values; (Harris, 1997),[8] an effect also noted as important in the sensitivity analysis for the Salford EH model (Chapter 4.4.3.1.).

[7] R_{si} of 0.17 m^2KW^{-1} used in all models.

[8] Everett (1985) also reports a significant disparity between modelled and measured floor U-values for a solid ground floor with 25mm edge insulation: measured heat-flow was about double that modelled, possibly caused by wrongful assumptions about ground conductivity and ground water content.

Overall, the cause of the disparity between the current models and the in-situ measured estimated whole floor U-value is unclear. The disparity is also more pronounced in the field-study than in the Salford EH. This might be because the Salford EH conditions were steady-state and might reflect the steady-state model assumptions (BSI, 2009b), including thermal mass equilibrium. As discussed in Chapter 2.3., floor U-value models have been created according to a theoretical and physical framework based on steady-state conditions and certain input assumptions. However the field-study - unlike the Salford EH - was subject to dynamic conditions and practical in-situ measuring issues, and alongside the input assumptions used, the ability of theoretical models to deal with this level of complexity is yet unknown. A conceptual difference between models and in-situ measurements might be a reason for such disparities. For instance, linear thermal bridging of the wall-floor junction is excluded in models, though in-situ measurements might be affected by the wall-floor junction heat-transfer. Another example is that theoretical floor U-value models consider the heat-transfer and temperature difference over a full year and that the thermal mass of the ground is negligible (and is hence excluded in models) (CIBSE, 1996, BSI, 2009b). BSI (2009b) considers the annual heat-transfer a good approximation of the average heat-flow in the heating-season (the period in which field-study measurements were undertaken) however it is unknown if this is indeed the case for suspended floors. CIBSE (1996) suggests the same for ground floors with '*an appreciable'* thermal mass delay but suggests that where there is a smaller thermal mass delay, seasonal temperatures should be used instead[9]. It is undefined if this applies to suspended ground floors.

To investigate the ground's thermal behaviour, the outputs of three heat-flux sensors placed on the ground in the void (two under sensor location 22 and one in location 5 - see Section 5.2.3.1.) were investigated. For each sensor on the ground in the void it was observed that the heat-flow (q, W/m^2) going into the ground did not equal the heat-flow coming from the ground[10] over the winter floor monitoring period of 13 days. As expected and in general near the airbricks, more heat was released from the ground over the monitoring period than transferred to the ground.[11] This is unsurprising given the exposure of the void to external temperatures through nearby airbricks and colder void surfaces, so the void temperatures are expected to be below the ground temperatures in this area in winter. Further away from airbricks, the direction of heat-flow was always from void to ground each day; though it is unknown (how much) of this heat was stored or transferred.

[9] CIBSE (1996) does not define what an appreciable or small thermal mass delay is. According to ISO-13370 (BSI, 2009b), the thermal lag for suspended ground floors are less *"because the ventilation heat flow has no time lag"* (p30) and suggests that suspended floors have a thermal mass delay of 0 months (though this could still include several days or weeks).

[10] This was observed outside the HFP01 instrument error margins of ±15% for ground heat-flux measurements.

[11] This depended from day to day, but overall heat-flow was from ground to void.

This suggests that in the observed locations, the ground thermal mass was not in equilibrium over the monitored winter period. However, these ground heat-flows were a small proportion of the overall room to void heat-flows when compared to the nearby sensor locations on the floor above: the total 13-day observed ground heat-flow near airbricks was just 2% to 4% of the heat-flow observed in location 22 above; and about 16% further away in location 5. This might indicate that the thermal mass effect in this suspended floor over the monitored period was a proportionally small driver in floor heat-transfer, and especially near airbricks. However further research and high-resolution long-term monitoring of both floor and ground heat-fluxes are required to reveal longer-term seasonal changes of the ground and to investigate whether annual heat-flow and temperature assumptions are a good proxy for the seasonal heat-flow for suspended ground floors as measured here in the field study.

Overall, it is clear that further research is required to understand which parameters and assumptions create a discrepancy between models and in-situ measurements, and how this gap can be bridged to create more robust models and more informative in-situ monitoring. This work is particularly important because significant differences between modelled and measured U-value estimates have implications for policy and retrofit-decision making as discussed in Section 5.4 and Chapter 7.4. Hence high-resolution and longitudinal sampling of a larger number of floors, including different dwelling types and orientation, different void depths and ventilation and those with different floor areas and with different *P/A*, are required to assess if these disparities are specific to the cases studied and/or the different models used and if they remain in a larger sample.

5.3.7. Void airflow and effect of sealing airbricks

5.3.7.1. Void air flow

As described in Section 5.2.3.2., one-directional void airflow was measured at high level (in between joists) and low levels (about 100mm from the void ground level) in void locations below location 6 (in line with the airbrick) and further away in floor void section 4 (near location 13 above) - see *Figure 44.* in Section 5.2.3. As can be seen from *Figure 55.,* the mean void airflow at low level near the airbrick (pink line) and further away (grey lines), were all generally low (i.e. 0.05 to 0.10±0.12 m/s, which is within the error margins of zero airflow). The mean void airflow at high level in front of the airbrick in location 6 was 0.44 ±0.12 m/s (instrument error), reaching a peak of around 1m/s ±0.12m/s in front of the central airbrick.

Figure 55. Plots the uninsulated void airflow (m/s) over time in front of the airbrick under location 6 at high level (red line) and low level (pink) and under location 13 at high and low level (dark grey and light grey respectively). The observed airflow at low level were all within margins of error from zero airflow; only one-directional airflow was measured however.

Section 5.3.1. suggested that the presence of sleeper walls might act as obstructions to the cross-flow movement of incoming colder external air further along in the void. This might also explain the low observed airflow in void section 4 at high and low level. However, as noted previously, the instruments only measured one-directional airflow: airflow from different directions would not have been recorded. Hence when low airflow was observed, it remains unknown if this was caused by low airflow in the main direction of the sensor or by low airflow in the void in all directions.

While reduced airflow velocity beyond a sleeper wall in a test cell was also observed by Harris (1994), airflow extent remains uncharacterised for the field study. Additionally, airflow might have been reduced by the isolation of the living room and kitchen floor void (by temporarily sealing the connecting openings), preventing cross-flow of air through the floor void sections.

Additionally, no positive correlation was observed between measured external wind-speeds at the back of the house and observed void airflow at the front of the house. This illustrates the complex relationship between void airflow, wind-driven pressure differences within the void and their distribution around the dwelling and the wind-speed measurement location.

Sealing of the airbricks seemed successful in the pre-insulated floor void with all sensors recording low one-directional airflow in the void (i.e. 0.04 to 0.09±0.12 m/s, i.e. within the error margins of zero airflow); not illustrated here. The effect of airbrick sealing on estimated U-values is discussed in the following section.

5.3.7.2. Sealing of airbricks and impact on U-values

This section tentatively supports hypothesis 3 ("*There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks.*"). In general, similar findings were observed as for the Salford EH as discussed in Chapter 4.4.4. and included a drop in U_p-values, especially pronounced near the airbricks, and a more even spread of U_p-values across the floor with airbrick sealing. Further away from the airbricks error margins overlap between sealed and open airbrick U_p-values - see *Figure 56.* A paired Mann-Whitney U (Wilcoxcon rank sum) test supported the third hypothesis when comparing the 26 point U-values with open airbricks and with sealed airbricks: Mann–Whitney W = 351, n1=n2= 26, $P < 0.05$ (0.00000003, paired); error margins are not taken into account in statistical tests.

The whole floor U-value of the airbrick sealed floor was 0.72 ±0.15 $Wm^{-2} K^{-1}$ (i.e. 0.57 to 0.87 $Wm^{-2} K^{-1}$, without joist adjustment).[12] This was a 31% whole floor U-value reduction with sealed airbricks and this reduction was about twice as much compared to the Salford EH (see Chapter 4.4.4). This disparity might perhaps be explained by exclusion of wind from the Salford EH though might also be over-or underestimated in the field study: the U-values had not settled at the end of the airbrick monitoring period (see below).

There is considerable uncertainty around each of the field study point U-values to be able to draw confident conclusions, this is because:

- only a 4 day period with sealed airbricks was measured due to time constraints - see Section 5.2.3.5.
- While ISO-9869 test criteria 2 was met (i.e. U-values settled within ±5% from the U-values obtained 24hrs prior), ISO-9869 test criteria 3 was not met, meaning that U-values did not settle within ±5% of the first 2/3rds of the data and the last 2/3rds of the data (whole days), meaning that according to the ISO-13370 no 'valid' U-values were obtained as they did not settle to within ±5% between the beginning and the end of the monitoring period- see Chapter 3.3.1.
- The not settling of U-values as described above might have been caused by the monitoring period being subject to different environmental conditions during pre/post sealing of airbricks, especially warmer external temperatures during the airbrick sealing monitoring period and this might have affected the above comparisons by affecting the thermal mass equilibrium of the ground- see *Appendix 5.D.* for variables pre/post airbrick sealing and discussion in Chapter 6.3.2.2.
- A larger variability in daily U-values affected overall larger uncertainties (18% to 23% depending on location on the floor) - see *Appendix 5.C.*

[12] Chauvenet's Criterion removed 2 to 6 hourly data points of a total of 96 hourly data points; this did not significantly affect estimated point U-values (0-6%) but reduced the *sd* of the daily U_p-value by 6% to 27% depending on point location on the floor - see Appendix 5.C.

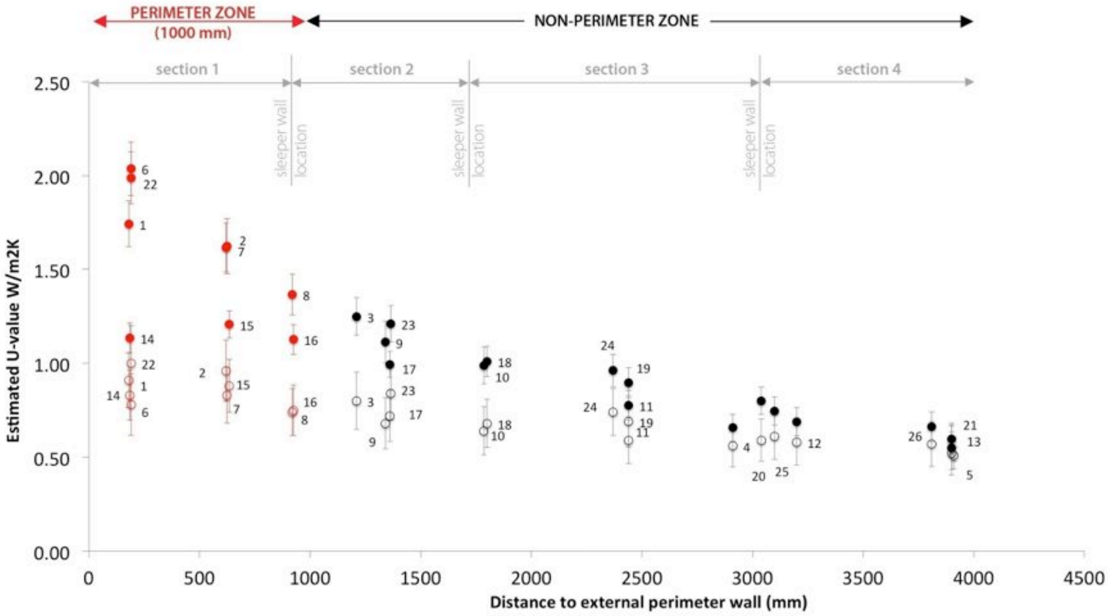


Figure 56. Plots the point U-values on the uninsulated floor with airbricks open (solid data points) and closed airbricks (outline data points) as a function of wall distance. Red data points are those located in the 1000mm perimeter zone; error margins were estimated with Equation 50. In general, a drop occurred in the same U_p-value after airbrick sealing, especially pronounced near airbricks (and outside estimated error margins). Further away from the airbricks, the effect becomes small and several error margins overlap. For relative reductions in each location, see Appendix 5.E.

5.3.7.3. Floor void conditions: short-term monitoring results

This section presents and discusses the results of the short-term floor void condition monitoring of the uninsulated floor and compares the findings with mould growth thresholds from literature.

Generally and as expected, the closer to the airbricks, the greater the void relative humidity (RH) and the colder the void - as summarised in *Table 29*. The field study's void condition over the monitored winter period was between mean void air temperatures of 9ºC ±0.4 ºC near the airbricks (void section 1) to 13ºC ±0.4 ºC further away from the airbricks (void section 4), with mean RH between 77%±4% and 62%±4% in void section 1 and 4 respectively.

Instrument error: ±0.4ºC and ±4% RH	Floor void section 1 (near airbrick)		Floor void section 2		Floor void section 3		External conditions	
Open airbricks								
Mean conditions	*ºC*	*RH (%)*	*ºC*	*RH (%)*	*ºC*	*RH (%)*	*ºC*	*RH (%)*
uninsulated floor	9	77	10	72	13	62	6.2	88
Sealed airbricks								
uninsulated floor	13	78	13	74	14	67	6.9	85

Table 29. Mean RH and temperature for the uninsulated field study floor void.

In general, the void conditions were in similar ranges to those reported by others in Scandinavia (though these were mostly insulated floors and in a different climate), see *Table 5., page 85*. Mean observed conditions further back in the floor void (section 4) were below critical mould growth thresholds reported in Chapter 2.7.4., *Table 4., page 82.,* which (depending on sources) suggest critical RH for mould growth between 75% to 95% for temperatures between 5ºC to 17ºC as observed in the field study void and for minimum 7 days duration. The higher mean RH nearer the airbricks in the field study however were close to or within the 75% RH threshold (threshold for 10ºC as suggested by Johansson (2012)) though were generally below the 80% threshold as suggested by Pasanen (2001) for the void temperature ranges observed in the field-study (10ºC-17ºC) and similar to Nielsen's (2004) and Hukka's (1999) thresholds of 78% to 80% respectively for >5ºC temperatures.

Given that conditions were measured near the ground in the void, observed conditions were also likely to be colder and with higher RH than if measured higher up in the void near the joists as also reported by Harris (1995). However if ideal conditions occur near the ground, mould growth could still occur on organic matter in the form of (saw) dust and organic dirt build-up over the years on the ground, posing a risk to occupant health (Kurnitski, 2000). No visual presence of mould-growth was found during the field-study and as can be seen from *Figure 57.*, there was significant variation in both void RH and temperature over the 18-day monitoring period: the minimum 7 day duration required for mould growth was not met and mould growth might be unlikely, based on these simplified comparisons. However, longer-term monitoring is clearly required: any absence of mould growth in this short-term study does not mean that there is no mould growth risk given that long-term monitoring is crucial (Pasanen, 2001) and seasonal bias is highly probable as winter mould growth risk is likely to be lower than during the summer season, as discussed in Chapter 2.7.

While it does not appear that short-term airbrick sealing over winter in the field-study would lead to excessive moisture build-up in uninsulated floor voids, in this short-term study, sealing of airbricks increased RH thresholds minimally (*Table 29.*) and this might increase the risk of mould growth when compared to the lower theoretical model growth risks and duration. As expected, due to the short monitoring period it is not possible to make firm conclusions about the effects of longer-term airbrick sealing in winter or in other seasons - further research is required. While the mean void air temperature was warmer near the airbricks and with similar RH pre-sealing, the sealed airbrick void condition was only monitored for four days. Further research is required with regards to the effect of the presence of oversite concrete, which might lead to drier void conditions than might be the case without ground cover. Additionally, as illustrated by *Figure 57.,* the airbrick sealing created more stable floor void conditions, potentially increasing the risk of mould growth ((Ridout, 2001), see Chapter 2.7.) While short periods with ideal conditions may lead to cumulative mould growth over time, fluctuating conditions might stop mould growth.

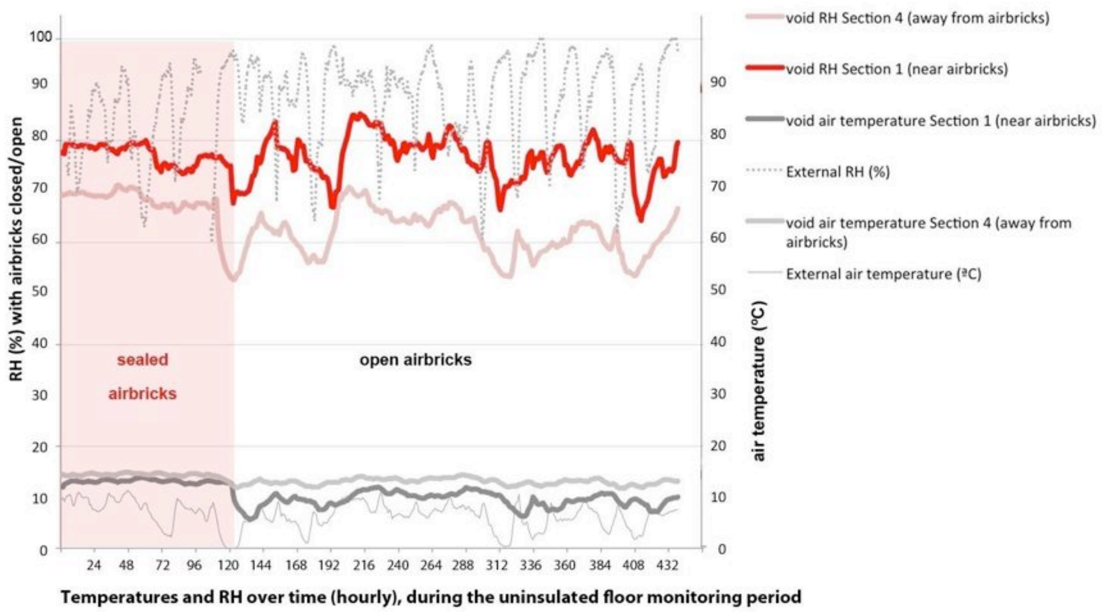


Figure 57. highlights that the RH and void temperature profiles show less variation after sealing the airbricks in the uninsulated floor and highlights the increased temperatures (light grey line), and reduced RH further away from the airbricks (pink line) compared to near the airbricks for a short period in winter.

In summary, since this study was undertaken over a short time-period it was unable to capture longer term seasonal trends, hence caution is especially recommended for short-term monitoring, because this could over-or underestimate mould growth risk depending on when data was collected. If short void monitoring periods are taken to be representative of the yearly floor void conditions, monitoring over winter - as was done here - might underestimate the mould growth risk, while only monitoring over summer might overestimate the risk. These observations demonstrated and verified the importance of monitoring long-term, including summer periods and monitoring void areas away from the airbricks as these areas are likely to have more stable conditions due to reduced ventilation and might become susceptible for mould growth. As such - and as expected - any findings remain inconclusive, and this includes the impact of the sealing of airbricks on the floor void conditions. For this reason the data also does not support comparison between floor void conditions pre/post insulation and is not reported in this thesis.

5.4. Implications for policy and retrofit decision-making

The field case-study illustrated that the estimated in-situ floor U-value might be significantly greater than assumed and modelled at present. As a consequence, the benefits of insulating the ground floor might be underestimated, as also noted by Everett (1985) for solid ground floor heat loss. For this field study, the superseded CIBSE-1986 model seemed to give a floor U-value estimate closer to the in situ measured whole floor U-value, compared to the current models. However, to test whether the CIBSE-1986 model outputs are a better predictor of actual floor thermal transmittance, further research and a larger sample of high-resolution in-situ floor heat-flux measurements of a variety of floors are needed to investigate model accuracy.
However, if the disparity between modelled versus measured U-values are more broadly confirmed in the pre-1919 housing stock, it would have significant implications for policy and retrofit decision-making: ground floors might be left uninsulated if the thermal transmittance and the benefit from insulating floors are underestimated, especially given the disruption to insulate these floors for a seemingly small benefit. Doing so might then bypass a significant reduction potential in space-heating energy.

Finally, there might be a significant U-value reduction potential associated with the temporary sealing of airbricks in winter. However, further research is required into the efficacy of doing so in a larger sample of floors and the impact on floor void conditions from airbrick sealing to avoid potentially increased mould growth risks and associated occupant health impacts.

5.5. Discussion and summary

In-situ heat-flow measurements were undertaken in an unoccupied field study house at high resolution in 26 locations on the floor and one location on a joist. Airbricks were sealed to investigate the effect of airbrick ventilation on observed U_p-values. This chapter addressed research question 2 (*"What is the in-situ measured thermal transmittance of floors and how does it compare to model predictions?"*, while also testing research question 1 in the field (i.e. *"How should in-situ suspended timber ground floor U-values be estimated?"*), building and reflecting on the research methods and techniques developed at the Salford EH.

As in the Salford EH, several hypotheses were tested and were supported by the field study analysis and findings, including that there was a large spread of U_p-values across the uninsulated floor (H1) and that perimeter U_p-values were greater compared to the non-perimeter zone (H2). While the whole floor U-value was decreased significantly with sealed airbricks (H3), though there were data quality issues which created considerable uncertainty around each of the field study point U-values for the sealed airbrick study - further research is required.

Furthermore, the presence of sleeper walls might act as obstructions to the cross-flow movement of incoming colder external air further along in the void. This was tentatively support by low recorded void airflow away from the airbricks in the present study. However, more research is required to determine whether this was a general phenomenon, or whether it was inherent to the instruments used (one-directional air flow only was measured) or to the study house (which also had temporary obstructed cross ventilation in the void). This might have implications for the installation of floor insulation, where perimeter insulation might be most effective; further research is required.

Similarly to the Salford EH, the field study reiterated that the use of only a few in-situ point measurements would highly likely under-or over estimate the whole floor U-value, depending on sensor placement. Additionally, comparing U-values estimated from models with the whole floor U-value estimated from in-situ measurements highlighted that current models might significantly underestimate the whole floor U-value. For the field study the in-situ measured whole floor U-value was twice the modelled values; similar disparities were found by Everett (1985) for a solid concrete ground floor with 25mm edge insulation. It is unclear what caused this divergence, however the superseded CIBSE-1986 model appeared to be a better predictor of the actual whole floor U-value of the field study; further research is required to investigate if this is the case for other studies.

It should also be noted that over-estimation of modelled values (some of the CIBSE-1986 outputs, depending on variables used) would overestimate the benefit of floor insulation and its payback. The generalisability of findings of case-studies is discussed in Section 3.4.4.

The field study also lead to practical insights, useful for future in-situ measuring studies. Those listed below are in addition to those already reported above or in Chapter 4.5.:

- Where ambient internal and external temperatures are measured and when adjustments are made for surface resistances, can influence U-value estimation. However in the field study these differences were within the margin of error. Additional air temperature and room airflow measurements might be helpful to investigate the thermal resistance of the surface boundary layer across the floor.

- In this field study, 12-13 days were sufficient for determination of uninsulated floor U-values. For the sealing of airbricks, a longer monitoring period than the 4 days allowed for in the field study is required to enable robust U-value comparisons and to allow for possible thermal mass equilibrium settling. However, the above monitoring periods may not apply to other measuring studies due to different environmental conditions etc. - further research is required.

- Multi-directional airflow equipment would be required for more robust analysis of void airflow.

- Monitoring floor heat-flux at high-resolution over a full year might aid understanding of theoretical model assumptions and concepts and to investigate the disparity between modelled and measured floor U-values.

Chapter 6: Measuring heat loss reduction potential of insulation interventions in the field and other considerations

6.1. Introduction

This chapter presents STUDY 4B and discusses the analysis and results of insulation interventions undertaken in the unoccupied field study house as described in previous Chapter 5. After measuring the heat-flow of the uninsulated floor, the floor was subject to two insulation interventions and was monitored at the same 27 locations on the floor pre/post interventions. The first intervention was EPS bead-filling of the entire floor void which - after removal- was followed by woodfibre insulation installation in between joists. In-situ U-value results are compared to the uninsulated floor, modelled outputs, other in-situ studies and building regulation requirements. A short intervention pilot study (STUDY 3) was undertaken prior to this study and is briefly described in this chapter with more information in *Appendix 6.A*.
Similarly to the uninsulated floor, airbricks were closed for a short duration to understand the airbrick ventilation effect on the observed U_p-values. In addition to in-situ heat-flux monitoring of the interventions, the field study's room air temperatures at different heights were also monitored for thermal comfort comparisons with theoretical thresholds. Blower door tests were also undertaken to investigate the impact of the interventions on the air leakage of the floor pre-and post intervention.

This chapter specifically addresses research question 3 ("*How does the in-situ thermal performance of a case study floor change after intervention measures?*"), while also testing ancillary research question 3.1 ("*What are the thermal comfort implications of insulated and uninsulated floors?)* and thereby contributes to supplementing knowledge of floor interventions and the impact on in-situ heat-flux measurements, floor airtightness and thermal comfort while also reflecting on the research methods and techniques developed in the previous chapters.

This chapter firstly introduces a brief exploratory study (STUDY 3) prior to the research design of STUDY 4B which describes the interventions prior to presenting and discussing the analysis and results of the field measurements of the insulated floors, in the following order: in-situ heat-flux results (Section 6.4.), thermal comfort issues (Section 6.5.), and pre/post intervention airtightness comparisons (Section 6.5.1.). Implications for policy and retrofit-decision-making are briefly discussed prior to the chapter summary and summary discussion of findings.

The diagram below gives an overview of the studies subject to this chapter's analysis and discussion, STUDY 3 and 4B are highlighted in red.

<table>
<tr><th>STUDY 1
Field study London</th><th colspan="2">STUDY 2
Salford EH</th><th colspan="2">STUDY 3
Pre-post pilot Manchester</th><th colspan="5">STUDY 4 (A & B)
Field study Ealing</th></tr>
<tr><td>Pilot study (2012)</td><td colspan="2">Initial study (2013)</td><td colspan="2">Pilot study: pre-post insulation intervention study (2013)</td><td colspan="5">Field study: pre-post insulation intervention study (2013-2014)</td></tr>
<tr><td rowspan="2">Field study, London occupied house; low-resolution monitoring: 2 locations on floor</td><td colspan="2" rowspan="2">Salford Energy House, environmental chamber; high resolution monitoring: 15 locations on floor</td><td colspan="2" rowspan="2">Manchester region, unoccupied house ; low-resolution monitoring: 4 locations on floor</td><td colspan="5">West London, unoccupied house; high resolution monitoring: 27 locations on floor. Additional monitoring of environmental variables, as well as monitoring of airtightness, floor void and thermal comfort variables pre-post interventions.</td></tr>
<tr><td colspan="2">STUDY 4 A
Field study Ealing (pre-insulation)</td><td colspan="3">STUDY 4 B
Field study Ealing (post-insulation)</td></tr>
<tr><td>Uninsulated</td><td colspan="2">Uninsulated</td><td>Uninsulated (pre)</td><td>Insulated (post)</td><td colspan="2">Uninsulated floor (pre)</td><td>EPS bead insulated floor (post)</td><td colspan="2">Woodfibre insulated floor (post)</td></tr>
<tr><td>Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td colspan="2">Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td>Sealed airbricks</td></tr>
<tr><td>March 2012- April 2012</td><td colspan="2">May 2013</td><td>September 2013</td><td>October 2013</td><td colspan="2">January 2014</td><td>End of January 2014-mid-February 2014</td><td>February-March 2014</td><td>mid-March 2014</td></tr>
<tr><td>Chapter 4</td><td colspan="2">Chapter 4</td><td colspan="2">Chapter 3 & 6/Appendix</td><td colspan="2">Chapter 5</td><td colspan="3">Chapter 6</td></tr>
</table>

Table 30. Summary table highlighting the subject of this chapter.

6.2. Exploratory intervention study (STUDY 3)

After in-situ heat-flux monitoring of the uninsulated floor as described in Chapter 5, two insulation interventions were installed and monitored in the case-study house. This main intervention study was supported by practical insights gained from a brief intervention pilot study (STUDY 3) as recommended by Robson (2011) and Barker Bausell (1994) and is briefly described below.

The exploratory pilot study was located in the Manchester region and took place between early to late September 2013 for the pre-insulation study (and early to late October 2013 for the post-insulation study). Floor insulation was donated by Knauf and the intervention was undertaken by owner Salford City West Housing Association and its subsidiaries. A 15 m^2 unoccupied living room floor was monitored at low-resolution with four in-situ heat-flux point measurements, four surface temperature sensors and external air temperatures. For the purposes of the exploratory study this resolution was sufficient. Given the season in which the study was undertaken, the purpose of the exploratory study was not to derive valid pre/post U-values but to test and reflect on research design and techniques to characterise floor interventions. An electrical radiator was set to keep internal temperatures at 21^{o}C internally, however internal temperatures were only a few degrees above external temperatures during this monitoring period (especially in the pre-insulation study); there was also loss of external temperature data and no valid U-values could be determined.

Insights gained from this exploratory study, which were carried forward in the main intervention study, included:

- the need for regular access and frequent data collection;
- sufficient blocking of direct solar gain onto the floor surface;
- importance of robust sensor location replication procedures to enable fixing sensors in the same location pre/post insulation;
- Presence during insulation installation to record installation quality issues, useful for later analysis;
- ensuring no other building works interfere with the intervention study;
- possible benefit of measuring other external environmental variables such as solar gain and wind-speed to understand pre/post changing environmental conditions and possible effect on pre-post results.
- For more detail and further insights, see *Appendix 6.A.*; for typical information sheet and informed consent sheets, see *Appendix 5.A*.

6.3. Insulation intervention study: research design (STUDY 4B)

The intervention study was an 'interrupted time series design' (Robson, 2011): in this case, floor U_p-values were characterised prior to floor interventions (see Chapter 5), with continued floor heat-flow measurements post-intervention, "*offering a unique perspective on the evaluation of intervention (or "treatment") effects*" (Glass, 2008). Establishing hypotheses is an important part of designing planned interventions to clarify causal relationships (Glass, 2008); six hypotheses, based on the research questions were developed; this study tested hypotheses 2 to 6, as set out in Chapter 3.4.1.

The number of interventions and the duration of the monitoring was limited by the winter heating season duration to ensure optimal external environmental conditions for monitoring. The research design centred around measuring (a.) the effect of insulation interventions on floor U_p-values (and their spread) and (b.) the effect of reduced airflow through the airbricks on observed heat-loss, by sealing of the airbricks.

Different methodologies were considered how to best undertake an intervention study (such as test-cell, occupied or unoccupied house) – as summarised in *Appendix 3.E.*, with advantages and limitations listed. The selection of floor interventions was based on the following criteria:

- A typical in between joist insulation intervention (see *Figure 7. option a)* and a least disruption method, without the need to remove all the floorboards, for example *Figure 7. option f or g*.
- Ability to attract industry sponsorship in the form of donated materials and workmanship to undertake the installation of interventions.
- Agreement with the home owner of the interventions.

The interventions which met the above criteria were (1.) filling of the floor void with EPS graphite coated beads and (2.) 100mm woodfibre insulation between the joists; findings are presented and discussed in this order. Only the living room floor was insulated due to access issues and presence of more extensive service pipes in the rest of the floor - see Chapter 5.2. The time-scale of the monitoring and intervention studies are listed in the gantt chart overleaf.

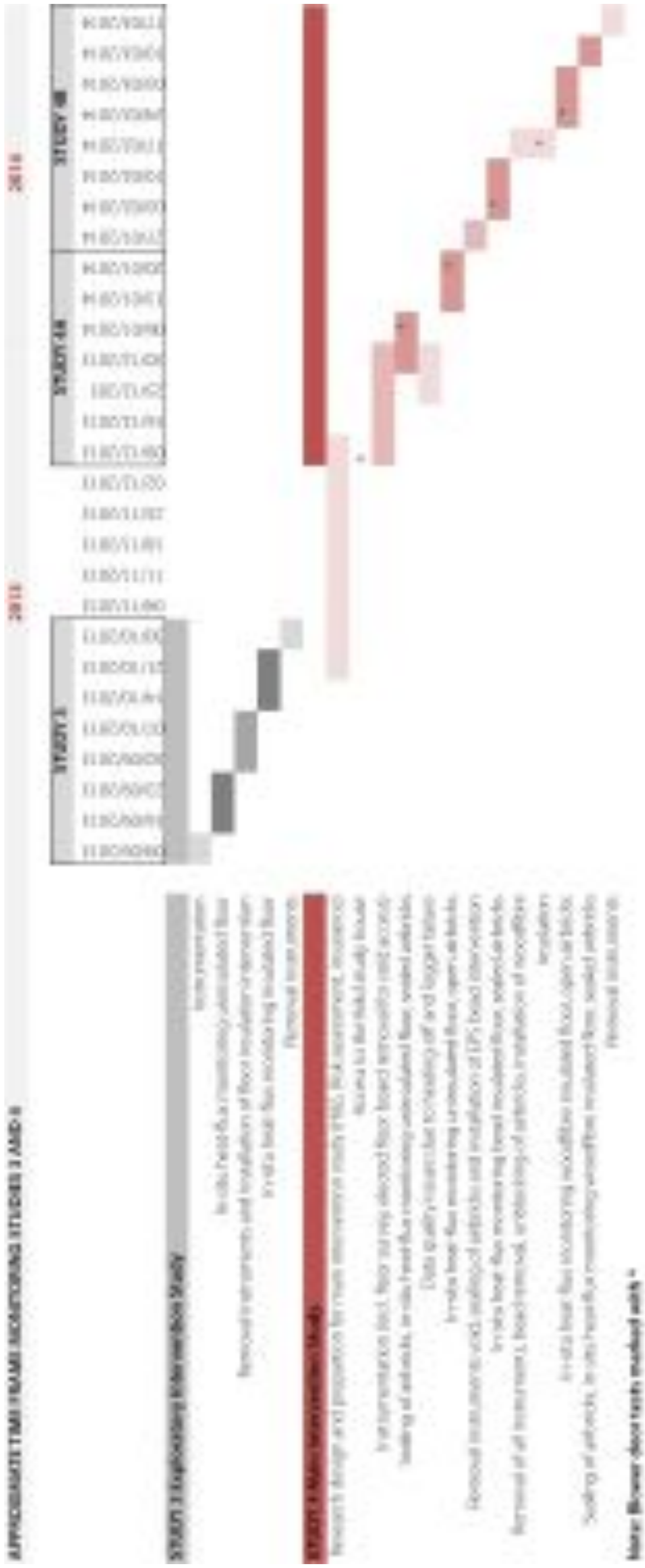


Table 31. Field study monitoring and intervention study timeframe

6.3.1. Description of insulation interventions

A brief description follows of the two insulation interventions undertaken. Between interventions, sensors either remained in place (bead insulation) or were removed and put back in the same location after installation (woodfibre intervention) - for sensor details and locations on top and below the floor, see Chapter 5.2.3, page 210. The case-study description can be found in Chapter 5.2.1, page 206. A control study house was obtained which was of limited use due to an unpredictable heating pattern, as described in Chapter 6.3.4.

As described in Chapter 5, isolation of the kitchen and living room floor voids was undertaken during the entire monitoring period to minimise the effect of the untreated kitchen floor on the living room floor intervention. This was because the kitchen floor void could not be accessed and the kitchen units and services could not be removed in order to insulate the kitchen floor void. As such the whole floor U-value pre/post intervention is determined from the living room floor only; as discussed in Chapter 5.2.

Industry sponsorship was obtained in kind from NBT and Downs Energy who both donated insulation materials and Downs Energy also undertook both interventions (and removal of the first intervention) on site under the author's observation. For associated research ethics and research management issues see Section 3.4.

Intervention 1: Full-filling of the void with EPS beads is an innovative solution intended to insulate floors without the disruption of lifting and re-fitting all of the floorboards. This insulation technique was used in a TSB Retrofit for the Future project as described by Baeli (2013, p37). The living room floor void was filled entirely with loose graphite coated EPS beads, after closing of the living room airbricks to avoid the EPS beads spilling out. Four floorboards - one in each section - were lifted to fill the 250 mm floor void (excluding 100mm joist height) using the same equipment as cavity blown EPS beaded insulation, without the binding agent/adhesive to allow for removal of the beads by hoovering them out. The beads were filled to the top of the joists - as shown in *Figure 58.* - and they easily filled gaps between services in the void and small spaces as well as between void sections due to openings in the sleeper walls. The EPS beads were donated and installed by Downs Energy; its BBA (2014) certificate states conductivity of $0.033 Wm^{-1}K^{-1}$. It is unknown however if the absence of glue increases the thermal conductivity due to possibly an increased number of air gaps remaining. After mechanical filling, manual smoothing of the beads between joists and manual top-up filling needed to happen to ensure filling to the top of the joists; this was visually assessed.

The whole floor was covered in a plastic sheet (over the instruments) and held down to contain void dust particles after mechanical blowing in of the beads. Filling the void took about half a day; instruments were left in place, apart from the airflow sensors. Beads were removed to enable intervention 2. There might be associated unintended consequences with sealing of airbricks - as described in Chapter 2.7.2. and Chapter 5.3.7.

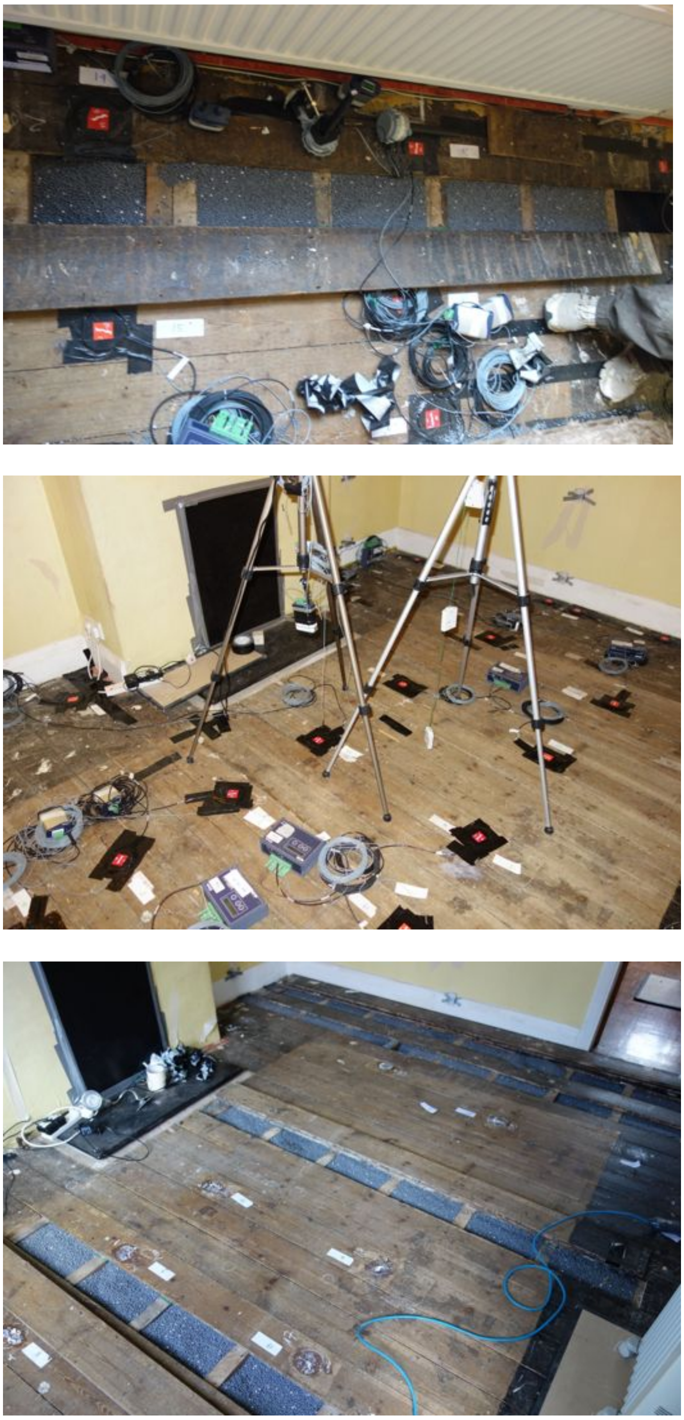


Figure 58. a., b. and c. the bead filled floor (a.) along the exposed perimeter wall, (b.) post-bead insulation with monitoring instruments in place and (c.) just before removal of beads.

Intervention 2: wood fibre insulation installation between joists: After bead removal, all instruments and floorboards were removed; the void radiator heating pipes were insulated[*] and 100mm woodfibre batts were installed between the joists, held by a tightly stretched and stapled breather membrane suspended over and under the joists. This is a typical insulation solution but generally the insulation is a flexible insulation such as mineral wool, which can be more easily inserted between unevenly spaced floor joists and often installed DIY (BRE, 2000, EST, 2005b).

However, mineral wool is not the recommended best practice insulation material choice by English Heritage (EH, 2010), and the home owner requested a natural material such as woodfibre or sheepswool; woodfibre was donated by NBT (Natural Building Technologies) with conductivity of 0.038 $Wm^{-1}K^{-1}$ (Pavatex, 2013) and installed by Downs Energy. Membrane sections were overlapped and taped with airtightness tape; insulation was fitted tightly between the joists to minimise any air gaps which could lead to increased convective heat loss (EST, 2006). Near the airbricks, the insulation was chamfered and installed against a roof ventilation 'lap vent' to allow airflow underneath (see *Figure 59.)*. Reduced insulation was also fitted where services encroached in the space between joists, as was the case near sensor locations 23 to 26 and in other unmonitored locations. Airflow between sleeper wall sections was likely significantly reduced due to the insulation being installed between joists, which were the largest openings between floor void sections prior to insulation. However, as discussed in Section 5.3.7., measured airflow in floor section 4 was low compared to the first section near the perimeter; as such both airflow sensors were moved from void section 4 to void section 1 and placed in front of the remaining airbricks - see *Figure 44.* in Chapter 5.2.3. After insulation installation, all sensors were replaced on top of the floor in the same position as the uninsulated and bead insulated floor monitoring design.

This final intervention was intended to be left in place permanently, hence it was the final intervention undertaken. See Chapter 3.4.3 and 3.4.4. regarding research ethics and generalisability. Information sheets, informed consents and risk assessment are provided in *Appendix 5.A.*

[*] While the central heating system was not being used in this study and out of order, as the insulation would remain in place, the water and heating pipes in the void were insulated to prevent risk of frost and undue lost heat from pipes in winter and to reduce risk of summer surface condensation.

Figure 59. a., b., c., d., e., clockwise from left to right: insulation of the void services and installation of 'lap vents' in front of the airbricks between the joists (a.); close-up of the chamfered woodfibre insulation to fit against the lap vent to enable airbrick airflow (b.); close-up of the lap vent prior to installation of chamfered insulation (c.); installation of wood fibre insulation in between the joists, held in a breather membrane over and under joists (d.) and (e.) overview of the floor surface after woodfibre insulation with monitoring instruments in place.

6.3.2. Error propagation and data analysis procedures

The same error propagation and data analysis procedures apply as set out in Chapter 5.2.4.

Between interventions, sensors either remained in place (bead insulation) or were removed and put back in the same location after installation (woodfibre intervention) - see Chapter 5.2.3. for locations and fixing methods. Hence for comparisons between the uninsulated floor and EPS-bead filled floor, contact, edge heat loss and instrument errors need not be included as these sensors remained in place – see *Equation 50.* in *Table 32*. However for comparisons with the woodfibre insulated floor, where sensors were removed and later the same sensors were re-located in the same place, contact error is likely to apply. Given that the same fixing method was used, edge heat loss is expected to remain the same between interventions; hence the final uncertainty estimate is calculated in accordance with *Equation 53. - see Table 32.*

Identified errors - see Chapter 3.3.4.3.	Applicable for each point-measurement without comparison	Applicable for each point-measurement when comparison of each intervention with airbricks open/closed; surface or air temperatures; and when comparing uninsulated point U-values with EPS bead insulated	Applicable when comparing point U-values from uninsulated floor or EPS bead insulated with woodfibre insulated floor
Intrinsic: Instrument error (calibration heat-flux and temperature sensors) ± 5%	± 5%	n/a	n/a
Extrinsic: Measuring condition error - **Edge heat-loss error**	±3%	n/a	n/a
Extrinsic: Measuring condition error - **Contact error**	±5%	n/a	±5%
Extrinsic: Measuring condition error - **Temperature location measurement error**	±5%	±5%	±5%
Natural variability U (inherent property, not a measurement error) - *sd* of daily Umean	± sd	± sd	± sd
Final estimated error	$\sqrt{5^2 + 3^2 + 5^2 + 5^2 + sd^2}$ *Equation 49.*	$\sqrt{5^2 + sd^2}$ *Equation 50.*	$\sqrt{5^2 + 5^2 + sd^2}$ *Equation 53.*

Table 32. Identified errors and applicability; for further detail see Chapter 3.3.4.3., page 124

Note that total measurement uncertainties were between ±11% and ±27% for the woodfibre insulated floor and larger for the bead-insulated floor (±17%-60%). However as point U-values were significantly reduced post-insulation, the larger proportional uncertainty generally represents only a small U-value range around the mean-point U-value.

6.3.2.1. U-value determination and removal of outliers

As there was minimal researcher influence, no Chauvenet's Criterion was applied for outlier removal in the field data for the insulated floors (as described in Chapter 5.2.4.2., Chauvenet's Criterion was applied for the uninsulated floor with open airbricks). Generally the blower door tests fell outside the monitoring periods used here for U-value estimation. For woodfibre insulation, the first 9 days were used in this analysis as all data met the ISO-9869 test criteria; after this period some missing data occurred and there were warmer external conditions.

The bead insulated floor was monitored for 15 days and point U-values were sought which met all three ISO-9869 test criteria (Chapter 3.3.1.). For the majority (17) of the point locations, 9 days of monitoring met all tests. However for 9 point-locations, shorter periods were used to estimate mean U-values - see *Table 33.* Using different time periods is not ideal given the different environmental conditions over different monitoring periods. This method however was justified because (a.) final estimated U-values (and *sd*) did not significantly differ between different monitoring periods, (b.) this ensured that all U-values were calculated from periods which met all ISO-9869 criteria for 'valid' U-values and (c.) this retained consistency of analysis in this thesis. In fact using 9 days of data would have made little difference in whole floor U-value determination - see *Appendix 6.B.*

Point location	monitoring period
U 24	5 days
U 5, U15, U16	6 days
U 21, U 26	8 days
U 14, U 23	12 days
U 13	15 days
All others:	9 days

Table 33. Summary of monitoring period for U-value estimation for the point-locations on the bead-insulated floor - based on meeting the ISO-9869 convergence tests.[†]

[†] Note that all but location 6 did not meet ISO test 2 at any monitoring time, but was ±6% after 9 days of monitoring, hence data was analysed after 9 days. Additionally, locations 15 and 16 met ISO test 2 after 6 days of monitoring, though ISO test 1 was just outside the ±5% threshold.

6.3.2.2. Changing environmental conditions over time

In field studies, it is not possible to have a perfect comparison between interventions because the monitoring campaign is limited in time (and heating-season bound) and the environmental conditions are unpredictable and not the same over time. For this reason, the interventions were undertaken in sequence and as close as possible together, as also done by other studies, see Byrne (2013) for example.

Environmental variables are inevitable confounding variables which influence the observed heat-flow, leading to issues of comparison and robust estimations of the actual effect of interventions (Anderson, 2003, Park et al., 2013): i.e. is the observed effect significant and is it due to the intervention taking place or are there are other confounding variables affecting the measured change?

Some studies compare pre/post intervention predicted versus actual energy use and noted that significant under-or over-estimations may occur due to actual occupant behaviour versus modelled assumptions (see for example Rosenow (2013) and Sunikka-Blank (2012). Other studies compare actual pre/post intervention building energy use over longer time periods to gain an idea of the efficacy of interventions; energy use might be adjusted for external temperature, energy prices and other variables (such as changes in household income and members), see for example Hirst (1986). Such studies are also affected by compensating behaviour such as for example changing occupant behaviour (Rosenow and Galvin, 2013). However as the field case-study was unoccupied and only accessible for one winter heating period, no long-term actual pre/post energy use data was available for comparison purposes.

Stevens (2013) and Byrne (2013) monitored in-situ wall U-values before and after interventions; Stevens (2013) makes no mention of any adjustments or presence of confounding variables which may have affected pre/post U-values, though heating degree day adjustments for heating energy use were made. Byrne (2013) undertook pre/post monitoring in close succession as was the case in this study and qualitatively assessed external air temperature differences to gauge how this may have affected heating energy-use.

In this study, long-term pre/post monitoring was not possible and the use of a control house was not very successful (as described in Section 6.3.4.). External variables (see Section 5.2.3.) were measured and were described qualitatively by average values for each variable and the distribution of values over the monitoring period (see histogram plots in *Appendix 6.D.)*. This enabled a qualitative comparison of the monitored environmental conditions pre/post interventions to evaluate the impact of possible confounders on the overall U-value changes as different interventions took place.

Table 34. gives an overview of the mean environmental variables during each intervention period and how they may have affected the estimated U-values pre/post intervention. The pre-insulation mean external air temperature was slightly warmer (0.8°C±0.14°C) than the mean external temperature during bead-intervention. While the rate of conductive heat-flow is proportional to ΔT, the reason for possible impacts of changing external temperature (and hence on ΔT) on estimated U-values is because of thermal mass time lag, which - if all the ISO-9869 tests are met - is likely to be negligible. Note that thermal conductivities also *"show some variation with temperature*" though this is very small for most materials (Winterton, 1997). Radiant heat transfer also varies with changing temperatures and colder surfaces (largest impact likely near the external environment), though radiant heat-flow quantities are unknown. Higher mean wind-speed was also observed during the bead-intervention, which might have under-estimated the efficacy of the intervention, especially along the perimeter. However, this is likely to have had a minimal effect as the bead intervention relied on sealed airbricks, though colder air may have infiltrated through gaps and cracks in the foundation wall. The exact influences of these changing variables in U-value estimation are unknown and remain unquantified.

The pre-intervention period was significantly colder (6.2±0.1°C) than the mean external temperature during the woodfibre intervention (7.9±0.1°C); the effect on U-value determination is unknown. There was also significantly increased mean external wind-speed and observed perimeter void airflow[‡] compared to the pre-insulation period and this might lead to under-estimation of the woodfibre efficacy due to over-estimation of U_p-value estimates along the perimeter, however the exact quantity is unknown.

‡ The void airflow was however measured closer to the external airbrick as a direct result of the woodfibre insulation intervention, compared to the pre-intervention void airflow sensor location.

The external ground temperature, likely affected by rainfall (not measured), air temperatures and solar radiation, followed the external temperature and was slightly warmer on average for the uninsulated and bead-filled floor; but was similar in temperature to the external temperature during the woodfibre insulation monitoring period - see *Table 34*. Solar radiation was also similar between the pre-intervention period and the bead-insulated floor but - as expected with longer days - was significantly higher during the woodfibre intervention. It is unclear - if- and how increased ground and external temperatures and solar radiation over the pre/post intervention periods might have affected U-value estimation. In all cases, the actual magnitude of the effect remains difficult to quantify. In addition, there might be increased heat-transfer to the ground from the floor during spring, as discussed further on page 260.

In summary, it has not been possible to ascertain how the pre/post intervention measurements might have been affected by other external changing variables; given that the magnitude of these effects cannot be quantified, it is unknown if these variables would (partially or fully) offset each other or not and how this may have biased the final estimated U-values for each of the intervention periods. In this qualitative assessment the influence of dynamic diurnal effects was excluded, as are seasonal thermal mass changes of the ground because no long-term monitoring could be undertaken. However, some hypotheses of possible seasonal thermal mass effect are presented on page 260.

Environmental conditions (Airbricks open)	Uninsulated (13 days)	bead insulated (9 days)	woodfibre insulated (9 days)
% of time ≤15ºC external (based on hourly data)	100%	100%	100%
Mean external temperature	6.2 ±0.1 ºC	5.4±0.1 ºCºC (9 days)	7.9 ±0.1 ºC (9 days)
Mean external windspeed	0.41 ±0.2 m/s	0.73 ± 0.2 m/s	0.79 ±0.2 m/s[§]
void airflow (below location 6)	0.44 ±0.12 m/s	assumed 0m/s (sealed airbricks & fully-filled void)	0.83 ±0.12 m/s[**]
Mean solar radiation	227 ±23 W/m^2	221 ±22 W/m^2	379 ±38 W/m^2
Soil temperature 1000mm away from house at 300 mm depth	7.1 ±0.1 ºC	6.2 ±0.1 ºC (15 days)	7.7 ±0.1 ºC
Possible confounding influences on estimated U-values?	Lower wind-speed and void airflow than during the insulation interventions may bias heat-flow lower than may have otherwise been the case; this means an under-estimation of the intervention impacts, particularly along the perimeter; though this is likely to have limited overall effect on the whole floor estimated U-value due to its contained impact and might be offset by other changing variables.	Increased wind-speeds, but sealed airbricks, so likely to have limited effect on U-value estimation; reduced external temperatures might change the thermal equilibrium of the ground and increase edge heat-flow, though it is unknown what the effect would be on whole-floor estimated U-value.	woodfibre insulation benefit may be underestimated near airbricks due to higher void airflow (and wind-speed) than when uninsulated but might be offset by increased external and ground temperatures and increased solar radiation: this might lead to warmer void conditions and changing ground thermal mass heat storage and might over-estimate the reduction potential from the woodfibre intervention[††], if longer-term thermal mass delays are not fully included in the monitoring period (see below). Overall the effect is unknown.

Table 34. presents the different mean environmental variables during the monitored intervention period. Mean data are based on daily data unless otherwise stated.[‡‡]

[§] Note that the mean void airflow measured in front of airbricks at low level is similar to the mean recorded wind-speed measured externally at 2.8m high. This is unexpected and might be explained by the location of the windspeed anemometer at the back of the house in a more protected area compared to the front of the house airbricks, which is more exposed and on the west/SW facade. The recorded external wind-speed may not be representative of the wind-speed at the front of the house. See also Section 5.3.7.

[**] Note that the void airflow, once woodfibre insulated, was measured closer to the void airbrick in order to measure the direct airflow under the insulation; hence direct comparisons pre-insulation airflow should be made with caution.

[††] No significant associations between heat-flux density and solar radiation or ground temperature were observed in this study.

[‡‡] Note that this is based on hourly or daily data during the associated monitoring period and may be slightly different from those reported in Chapter 6.5 as those are based on occupied hours only as the basis of thermal comfort assessments.

Seasonal thermal mass effects

There are short-term daily thermal mass effects of the ground and foundations walls as well as slow-response seasonal effects as noted by Emery (2007) for solid ground floors. The day/night thermal mass effects as well as thermal storage changes after interventions were likely captured by the relatively long monitoring times (as attested by data meeting the ISO-9869 tests, with exception of the sealed airbrick interventions).

However, slow-response dynamic seasonal thermal mass effects remain uncharacterised as heat-flow was monitored over one heating season only and over short periods. Yet, it is highly likely that such seasonal effects influenced the observed heat-flow, especially towards the end of the monitoring period.

Both Shipp (1985) for a basement floor and Delsante (1990) for a solid ground floor observed that heat-flow to the ground was generally reduced during summer and autumn, with increasing heat-flow during winter and peaking in spring. This might be explained by the thermal capacity of the ground, which is warm after summer, releasing some stored heat to the slab and buffering heat-flow from the floor slab in autumn. Gradually as the ground's thermal store is diminished, this might lead to increased heat-flow from the floor to the ground during winter and into spring. This might mean that monitoring periods during autumn might lead to lower estimated solid ground floor U-values compared to mid-winter, while spring monitoring might lead to higher solid ground floor U-value estimates compared to mid-winter monitoring.

Based on the above, generally, it might be expected that:

- During spring and summer the warm external air brought in via airbricks warms up the void, and where the ground temperature is less than the void air temperature; the ground thermal mass stores heat which will be released when the conditions reverse (e.g. at night or during changing seasons). This process might also lead to increased humidity in voids - see Chapter 2.7.
- During early autumn, when cold external air is brought into (sections of) the floor void; the void temperature is likely to drop below the ground temperature and the ground thermal mass will generally 'release' stored heat to the void. This will also be influenced by heat-flow from above, depending on the internal conditions and dynamic diurnal patterns.

However, further longitudinal heat-flux monitoring of the floor and ground are required to investigate if these trends are similar for suspended ground floors (and in different locations under the suspended floors).

6.3.3. Thermal comfort field data collection

As discussed in Chapter 2.5., avoiding thermal discomfort is important because it might lead to increased energy use to compensate local thermal discomfort (Rock, 2013) by increasing room air temperatures (Olesen, 1979). An in-depth thermal comfort study and impact of discomfort on compensating energy-use was not within the remit of this research. Additionally, as the field study house was unoccupied, people's thermal comfort responses were also excluded from this study. Instead floor surface and room air temperatures were monitored during the pre/post intervention studies and during sealing of the airbricks to enable comparison of these interventions to different theoretical metrics for thermal comfort. In this study, the ASHRAE (2013), BSI (2006) and CIBSE (2015) 19ºC floor surface temperature threshold and the 3ºC head-feet temperature difference threshold when seated (0.1m-1.1m) and standing (0.1m-1.7m) were used as thermal comfort thresholds - see Chapter 2.5, page 65. A higher 7ºC head-feet temperature difference threshold was not applicable as monitored air temperatures were all below 23.5ºC (Olesen, 1980).

CIBSE (2015) sets out room 'operative temperatures' in winter of 22ºC to 23ºC for general thermal comfort in living rooms and as low as 17ºC in kitchens and bedrooms. The term 'operative temperature' (t_o) refers to a combination of room air temperature and the mean radiant temperature and is related to the radiant and convective heat transfer coefficients - see *Equation 54.:*

$$t_o = \frac{h_c t_a + \bar{h}_r \bar{t}_r}{h_c + h_r}$$

-Equation 54. (see BSI (2002) 7726) , where t_a is air temperature; t_r is mean radiant temperature; h_c and h_r are the heat-transfer coefficients by convection and radiation respectively (see Chapter 2).

Operative temperature is most practically estimated as the average of air and mean radiation temperatures, where airflow and the difference between air and radiant temperatures is small (<0.2m/s and <4ºC respectively) (BSI, 2002). Additionally, air temperature can be close to operative temperature, especially in well-insulated spaces and away from radiant heat sources (solar gain, radiators) (CIBSE, 2015, BSI, 2002). Despite operative and air temperatures not being the same, for the purpose of this PhD air temperatures were used due to air temperature sensor availability, leading to approximate comparisons with theory only.

Much of the earlier research by Olesen (1977, 1979), Munro (1948) and Billington (1948) also use air temperatures instead of operative temperatures. Eltek Type U thermistors (±0.1°C) were placed in the middle of the living room at 0.1m, 0.6m, 1.1m and 1.7m in accordance with BS-7726 (BSI, 2002) and after Gauthier (2014). Surface temperatures were also monitored across the floor for the purpose of U-value estimation (see Chapter 5.2.3.); middle of the floor surface temperatures were used for theoretical thermal comfort threshold comparisons. For practical and resource reasons, the associated thermal comfort implications of room airflow and draughts were excluded.

The living room was heated to reach 21°C, just below the CIBSE (2015) benchmark of 22-23°C for living rooms, however the lower thermostat settings in this study resembled those reported by Shipworth (2011) and Huebner (2013) in larger studies, as discussed in Chapter 5.2.3. For thermal comfort comparisons, all data were analysed at hourly intervals during 'occupied' time (i.e. excluding data when the heating was off).

6.3.4. Intervention study limitations

Intervention study limitations and issues are identified below. These are in addition to the limitations discussed in Chapter 5.2.3.5. for the uninsulated field study.

- **Changing environmental conditions:** Monitoring interventions in field studies are subject to changing environmental conditions over time. Some environmental variables were measured and a qualitative evaluation was undertaken of how the pre/post intervention measurements might have been affected by other external changing variables. However, it was not possible to ascertain the magnitude of these single or combined effects, while dynamic diurnal effects and seasonal thermal mass ground effects were excluded. Use of a control property was not very successful - see below. There was also some loss of external wind-speed data due to battery leaks in March, limiting comparisons further.

- **Unsuccessful use of a control property:** a nearby control floor was considered useful to enable the understanding and interpretation of the interventions in changing environmental conditions. As such, two heat-flux sensors were located on the floor perimeter of a property in the same street with the same orientation as the field case-study.

However the monitoring of heat-flow in the control property to determine valid U-values was problematic for several reasons: (a.) unpredictable heating pattern by the occupant (b.) this lead to average room air temperatures of just 14.1±0.35 °C and low surface temperatures of around 12±0.1 °C (c.) only two floor locations could be observed due to furniture placement, one of which was near an uninsulated radiator pipe. These influences lead to fluctuating heat-flow and U_p-values not meeting the ISO-9869 test criteria (and hence no valid U_p-values could be derived during the short intervention time frames for comparative purposes). These confounding variables inhibited isolation of the influences of the external environment on observed heat-flow which also influenced the main intervention study. This highlighted the importance to 'control' the heating pattern; and ideally more than one control site to account for spatial occupancy and temporal issues (Anderson, 2003). However, a general comparison of heat-flow trends in the control house and field-study house was still useful (see Section 6.4.1.).

The field-study kitchen area was also not considered suitable as a control: measurements in the kitchen were limited by room access and kitchen cupboards (see *Figure 44.* in Chapter 5.2.3.) and the lack of airtightness of the room (e.g. gaps around single glazed windows and the external door, a room airbrick vent and a cat flap) lead to difficult to control space-heating. In addition, the kitchen would likely have been affected from the interventions taking place in the living room.

- **Void airflow was not measured in the same locations pre/post interventions:** The airflow sensors were removed prior to bead filling the void due to their fragility and given that airbricks would be closed and the void fully bead-filled, no or low airflow was expected in the void. Secondly, the observed airflow at the back of the floor in void section 4 was low (see Chapter 5.3.7.); as such the two airflow sensors in floor void section 4 were re-located in front of the airbricks at high level below sensor locations 1 and 22 for the woodfibre intervention (see *Figure 44.* in Chapter 5.2.3.); the airflow sensors in location 6 were placed in similar high and low positions as the pre-intervention monitoring period. However, due to the airbrick locations in between joists, insulation installation was chamfered to allow airbrick airflow, and this was aided by installation of lap vents (see *Figure 59.)*; this is likely to have affected airflow coming into the void and created differences between pre/post woodfibre intervention study comparisons.

- **Short-term floor void monitoring only could be undertaken:** the literature review in Chapter 2.7. highlighted the seasonal impact on floor void conditions, with typically an increased moisture risk during summer than in winter. Hence ideally voids are monitored for at least one year. However, due to limited access, no longitudinal floor void study pre/post insulation could be undertaken - as described in Chapter 5.2.3.5. If short void monitoring periods are taken to be representative of the yearly floor void condition, monitoring over winter - as was done here- may underestimate the mould growth risk, while only monitoring over summer may overestimate the risk. In summary, short-term measurements were not a good indicator of floor void conditions: variables are influenced by the seasons and hence longer term monitoring is required. As such, general conclusions from short-term observations for the field study could not be drawn with regards to the impact of interventions on void conditions and mould growth risk and as such no results are reported.

- **Limited thermal comfort study:** due to undertaking interventions in an unoccupied house, no occupant thermal comfort surveys could be undertaken to assess the thermal comfort impact of the uninsulated floor and post-insulation. Instead, room air temperatures were monitored to allow for comparison with theoretical thresholds - as described in Section 6.3.3.

6.4. Impact of interventions on floor heat-flow

This section presents and discusses the general impact of the interventions and the in-situ estimated whole floor U-values, prior to model and literature comparisons. This is followed by discussion of the spread of U-values, void airflow measurements and airbrick sealing alongside other considerations of interest.

6.4.1. General assessment of intervention impact

Despite the control house being subject to low internal temperatures and an erratic heating pattern over the monitoring period (see Section 6.3.4.), in general several trends of the intervention impact in the field study can be observed and are illustrated by *Figure 60.*, which plots daily heat-flux density q (W/m^2) for the control house and for two locations in the field study over the 2 month intervention monitoring period; both control and field study house were subject to similar environmental conditions.[§§] The main trends observed were:

1) When comparing the variability of the daily heat-flux density q (W/m^2) in the field study (grey lines) compared to the control (red line), the control shows significantly less heat-flow variability at the same time as insulation interventions occur. Overall, this means that the variability of the heat-flow is highly likely associated with the floor interventions, to which the control house was not subject.
2) In general, all three lines show a similar daily pattern in peaks and troughs, suggesting that these are associated with external environmental conditions influencing the heat-flux density in these different locations in similar ways (including air temperatures, which were the same for the field study and the control property).
3) Despite differences in environmental conditions during the interventions, the insulation interventions seem to have a significant impact on the observed heat-flux density.
4) Sealing up of the airbricks also had a significant effect on heat-flow reduction of the uninsulated floor (and was inherent to the EPS bead insulated floor to the front of the house) - see discussion in Chapter 5.3.7. *Figure 60.* also indicates a significant impact for the woodfibre insulated and airbrick sealed floor in location 6 near the airbrick, but not in location 10, away from the airbricks. Overall, no significant difference was observed for the whole floor U-value of the woodfibre insulated floor pre/post airbrick sealing (see Section 6.4.2.2.)
5) Poor insulation and low space heating in the control house as observed here, meant that a floor could have similarly low heat-flow comparable to an insulated floor, but this is likely to have significant thermal comfort implications.

[§§] Some localised wind-speed effects may have been different between the two dwellings given their slightly different external obstructions and position in the same street (though both had the same orientation).

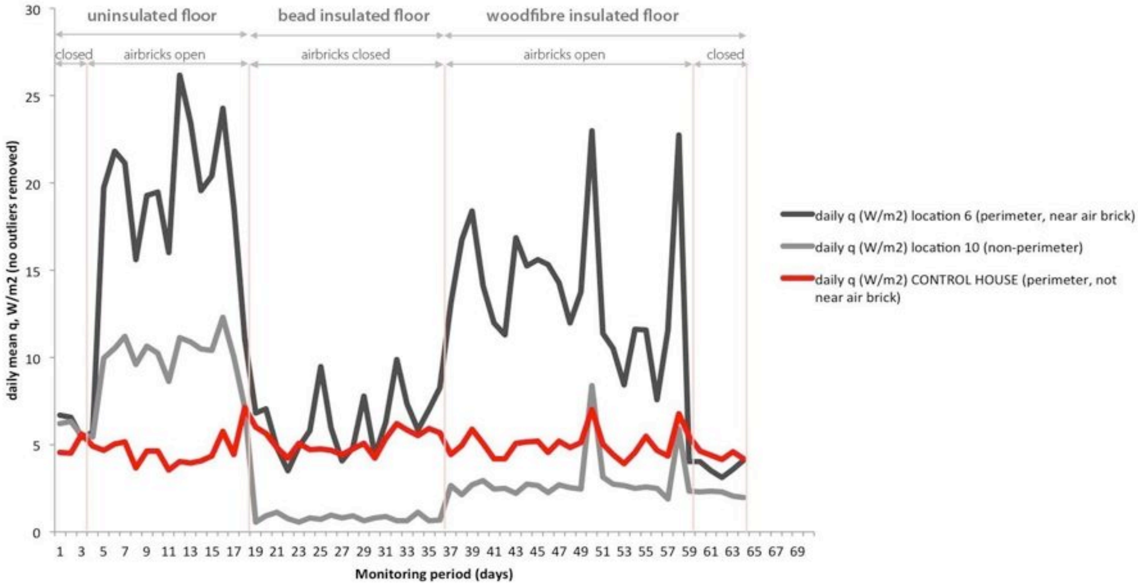


Figure 60. distinguishes the impact of interventions in the field study on in-situ measured mean daily heat-flux density (q, W/m²) in the perimeter area (location 6, dark grey line) and in the centre of the floor (location 10, light grey line) and in the control house (in red, perimeter zone) over the entire monitoring period. Similar trends exists between peaks, suggesting that this may be associated with external environmental conditions. Outliers were included in the graph and based on the full monitored period for each intervention.

6.4.2. Impact of interventions on whole floor U-values

Using the same weighted area summation techniques as discussed in Chapter 4.4.2.3., with identical area allocation to each heat-flux sensor as per the uninsulated floor (see *Figure 52.)* lead to an estimated whole floor U-value for the woodfibre insulated floor of 0.36 ±0.07 $Wm^{-2}K^{-1}$ and bead insulated floor of 0.09 ±0.03 $Wm^{-2}K^{-1}$ - see also *Table 35*. This excludes adjustments for joists for reasons as previously discussed in Chapter 5.3.2. Note that for the uninsulated floor, the joist presence lead to slightly increased thermal resistance; while for the insulated floors the joists become thermal bridges (EH, 2010) and are areas of reduced thermal resistance. For the bead insulated floor the U-value was increased by about 6% in the joist[***] location (with EPS underneath) compared to the better insulated location nearby[†††], though such small joist adjustment had no effect on whole floor U-value estimation (and was within the margins of estimated error). The addition of about 250mm EPS beads below the joists in the bead insulated floor lead to an estimated U_p-value reduction of 64% in the joist location compared to the uninsulated floor joist. However as the proportional reduction is location specific, this reduction might not be representative of the rest of the floor and might be underestimated as it was measured in the non-perimeter zone where U_p-values were lower.

Contrary to this, the estimated U-value in the uninsulated joist location for the woodfibre insulated floor was about double of the estimated U-value in the nearby insulated location and this did have a more significant effect on the whole floor U-value: an increase from 0.36 ±0.07 $Wm^{-2}K^{-1}$ without joist adjustment to 0.40 ±0.08 $Wm^{-2}K^{-1}$ after joist adjustment. Given that the joists remained uninsulated for the woodfibre intervention with only the addition of a thin breather-membrane, the joist U-value pre-insulation was, as expected the same as the post-woodfibre insulation (0.51 ±0.08 $Wm^{-2}K^{-1}$ pre and 0.51 ±0.07 $Wm^{-2}K^{-1}$ post insulation). Despite the impact of joist presence on the whole floor U-value, no adjustments were made due to the location specificity of the observed heat-flow reduction and to allow for comparison with the uninsulated whole floor U-value (which also excluded joist adjustment - see Chapter 5.3.2.). Joist presence was also excluded in models for comparison purposes.

[***] Joist U-value estimated near location 13 and after 8 days when all ISO tests were met for bead insulated floor for joist location.

[†††] This increase had no significant impact on the whole floor U-value determination: a small increase in U-value for 12% joist proportion of the floor is a small proportion of a floor with a low U-value.

Compared to the uninsulated in-situ estimated whole floor U-value, this field study observed a 65% mean floor U-value reduction after woodfibre insulation and a 92% mean reduction after bead filling the void -see *Table 35*. The insulated U_p-values differed significantly from the uninsulated U_p-values in support of the first part of hypotheses 5 (*"There will be a significant decrease observed in thermal transmittance after insulation installation"*): Mann–Whitney W = 351, n1 = n2 = 26,P < 0.05 (0.00000003, paired) for the bead insulated floor and Mann–Whitney W = 349, n1 = n2 = 26,P < 0.05 (0.00000009, paired) for the woodfibre insulated floor.

	uninsulated floor	**woodfibre insulated floor**	**bead insulated floor**
whole floor U-value ($Wm^{-2}K^{-1}$)	1.04 ±0.12	0.36 ±0.07	0.09 ±0.03
% uncertainty	12	18	31
% reduction compared to uninsulated	-	**65 %**	**92 %**
% Reduction when taking Min and Max U into account		54-75%	88-95%
Min U ($Wm^{-2}K^{-1}$)	0.92	0.29	0.06
Max U ($Wm^{-2}K^{-1}$)	1.16	0.43	0.12

Table 35. comparison of whole floor U-values and proportional U-value reduction based on in-situ measured values; excludes joist presence.

Uncertainty values listed in *Table 35*. illustrate that as the floor's U-value decreased, the error margins increased: from ±12% for the uninsulated floor to ±18% for the woodfibre insulated floor and ±31% for the bead-insulated floor. While an overall ±31% uncertainty is large, this larger proportional uncertainty generally represents only a small U-value range around the mean-point U-value - as also illustrated by *Figure 66.* in Section 6.4.3., page 277.

6.4.2.1. Impact of using air temperatures versus surface temperatures for U-value estimation

As discussed in both Chapter 4.4.5. and Chapter 5.3.3., different U-values were estimated for the uninsulated floors depending on which internal room temperatures were used to represent the ambient room temperature for U-value estimation. It was found that U-values derived from air temperatures decreased when the height of the measured air temperatures increased, corresponding to the observed temperature gradient.

In general, these findings remained for the insulated floors, though in the case of the bead insulated floor, the U-values were so small that no significant differences occurred: the impact of the R_{Si} addition on well-insulated elements has less of an impact on well insulated elements compared to uninsulated elements. The less insulated the element is, the smaller its thermal resistance and hence the greater the proportional impact of adding a large R_{Si}. This is illustrated by *Figure 61.* for location 10, where the addition of the R_{Si} is 17% of the estimated R-value when uninsulated, but just 5% and 1% when woodfibre or bead insulated respectively.

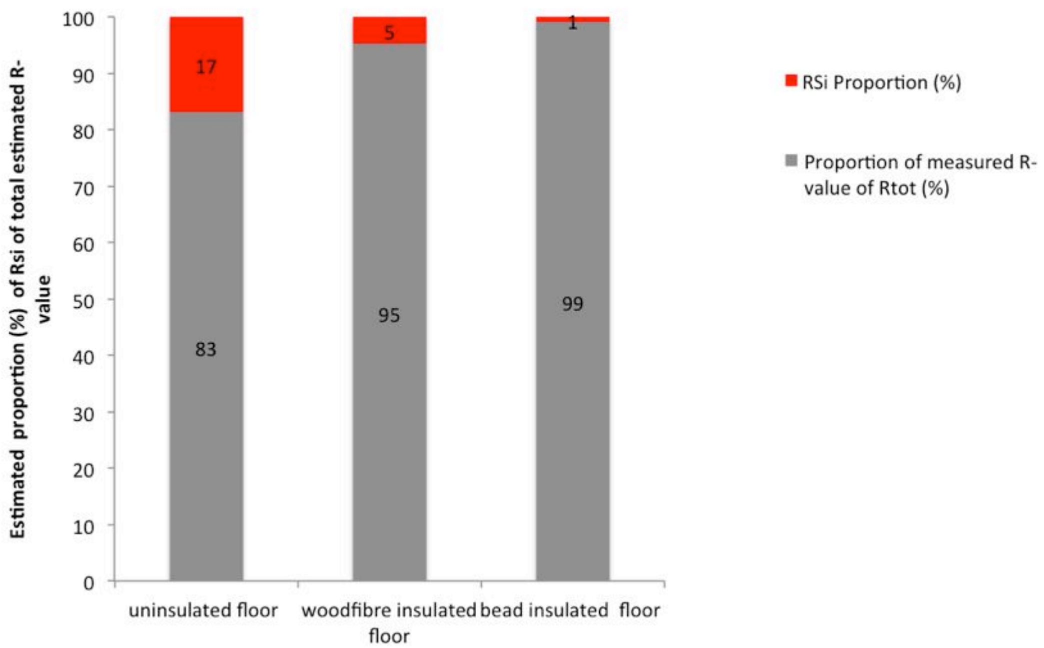


Figure 61. illustrates for the field study the estimated proportion of R_{Si} of the total R-value in location 10 on the floor when uninsulated, woodfibre and bead insulated.

6.4.2.2. Void airflow and sealing airbricks during the woodfibre intervention

Chapter 5.3.7. described the challenges of measuring void airflow in the uninsulated floor. Additionally, sensors were removed for the bead-insulated floor as the sealing of the airbricks was inherent to the intervention in order to contain the beads. For the woodfibre intervention all sensors were placed in front of the airbricks due to the low observed airflow away from the airbricks and the insulation placement between the joists.

As can be seen from *Figure 62.*, during the woodfibre intervention, the mean void airflow (at high level) near the two exposed airbricks was similar[‡‡‡](0.75 ±0.12m/s in location 6 (red line) and 0.80±0.12m/s for location 13 (dark grey line)). The average void airflow under location 1 (light grey line) was slightly lower due to its protected location (0.64±0.12m/s). The mean void airflow at low level (location 6, pink line) remained within the margin of error from zero (i.e., 0.11±0.12m/s, denoted by the grey zone around the pink line). However as described in Chapter 5 this observed airflow was one-directional and not all airflow was measured; in particular, data do not reflect that the airflow in the direction of orientation might have been low, while higher in other directions.

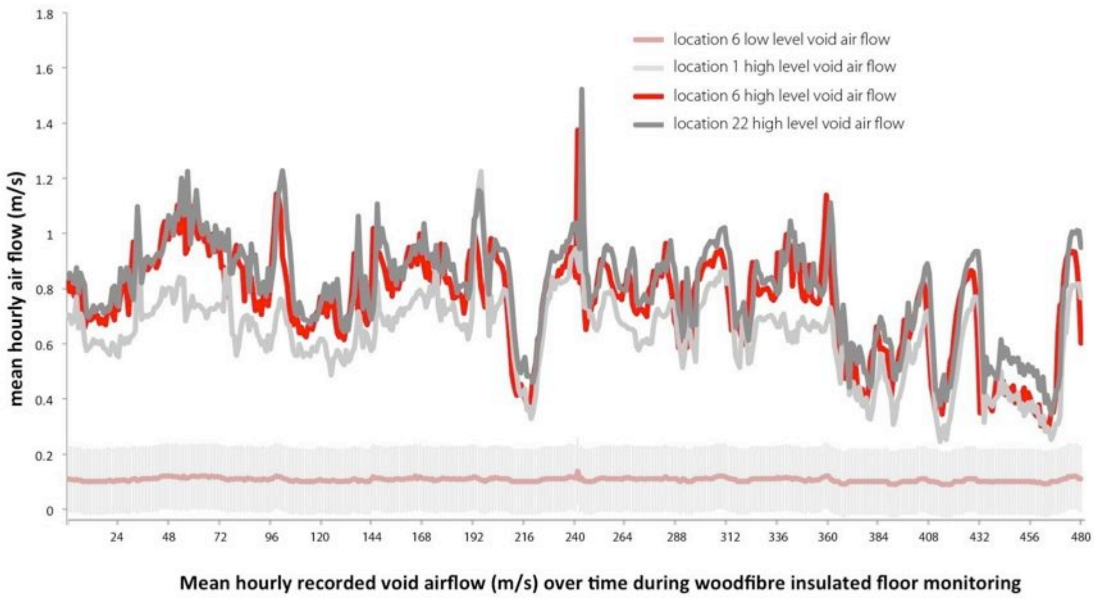


Figure 62. Plots the void airflow (m/s) in the front of airbrick under location 1 (light grey), location 6 (red, high level and pink, low level) and under location 22 (dark grey) during the woodfibre intervention. The grey zone around the pink line indicates the ±0.12 m/s instrument accuracy for that low-level location.

[‡‡‡] Note that this is the mean for the entire 15 day monitoring period; which is slightly less than for the 9 day period as used to estimate U-values as reported elsewhere.

The sealing of the airbricks during the woodfibre insulated floor was slightly less successful than for the uninsulated floor with mean void airflow of 0.13±0.12m/s in location 6 (high level). This might have affected the observed heat-flow during the sealed airbrick monitoring period - as discussed below. Airflow was <0.09±0.12 m/s in the other void locations. Heat-flow monitoring of the woodfibre intervention with sealed airbricks was undertaken for 6 days towards the end of the winter season and data quality was compromised due to a limited monitoring period and by changing environmental conditions over this period.

Different environmental conditions pre/post sealing of airbricks included doubling of solar radiation and increased external ground temperature post-sealing; this is likely to have affected the comparisons and actual measurements, though its exact effect and quantity is unknown - see *Appendix 6.C.* The ISO-9869 test criteria were generally met after 3 days near the perimeter and 5 days elsewhere. Of 5 days data (120 hours), the sealed airbrick woodfibre data had between 1 to 7 hourly data points removed caused by researcher influence with Chauvenet's Criterion. However, there were large uncertainties around the estimated point U-values caused by large daily variations in U. This lead to large estimated measurement uncertainties in U-value estimations: the whole floor estimated U-value of the woodfibre insulated floor with sealed airbricks was estimated at 0.33 ±0.24 $Wm^{-2}K^{-1}$ (so 0.09 to 0.57 $Wm^{-2}K^{-1}$) and while this is 8% below the pre-sealed whole floor U-value of 0.36±0.07 $Wm^{-2}K^{-1}$, the large post-sealing uncertainty means that this difference falls within the margins of measurement uncertainty. These results are likely associated with less ideal environmental monitoring conditions associated with changing external variables towards the end of the heating-season. As such hypothesis H3 and H3a could not be tested for the woodfibre insulated floor. ("*There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks*' and H3a: "*this effect will be proportionally smaller in insulated than in un-insulated floors*".). The impact of the airbrick sealing is likely to mainly affect the perimeter zone U_p-values due to insulation installation between joists, sleeper wall presence and previously observed low airflow away from the airbricks (see Chapter 5.3.7.).

6.4.2.3. Estimating a whole floor U-value with fewer point measurements

Similarly to the Salford EH and the uninsulated field study floor (Chapter 4.4.2.5. and Chapter 5.3.4.), measuring in just a few point locations would also highly likely lead to significant over-or underestimation of the whole floor U-value of insulated floors. This was especially pronounced for the woodfibre insulated floor due to the still significant spread of U_p-values across the floor (see Section 6.4.3.): just 79 pairs or 25% of the 325 possible pairing of U_p-values had overlapping error margins with the whole floor U-value estimated error margins. However, due to the reduced spread of U_p-values for the bead insulated floor, 50% (or 162) of paired locations would overlap with the whole floor U-value estimated error margins; the uncertainty of the estimated U-value associated with low-resolution measurements would be slightly reduced in this case.

There were 15 paired U-values where their average was the same as the bead insulated whole floor U-value; compared to just three for the woodfibre insulated floor. No single sensor location was found to be representative of the whole floor U-value across pre/post interventions. However, pairing of sensor locations gave 17 combinations (from a possible 325) which gave estimated mean U-values within uncertainty estimates for each of the interventions and the uninsulated floor - see *Table 36.*

Furthermore, slightly different estimates of the efficacy of interventions could be obtained depending on where paired measurements were observed - as illustrated by the proportional U-value reductions in *Table 36.:* U-value reductions were between 67% to 73% and 91% to 95% for the woodfibre and the bead interventions respectively, which is slightly above the 65% mean U-value reduction achieved from the area-weighted summation of 26 U_p-values for the woodfibre insulated floor, but similar to the 92% for bead-insulated floor.

sensor pairing		**mean U un-insulated**	*Error (±)*	**mean U Woodfibre insulated**	*Error (±)*	**mean U bead insulated**	*Error (±)*	**woodfibre reduction**	**beads reduction**
		$Wm^{-2}K^{-1}$						%	
HF8	**HF4**	1.02	*0.13*	0.30	*0.06*	0.08	*0.02*	**71**	**93**
HF8	**HF5**	0.96	*0.13*	0.32	*0.06*	0.09	*0.02*	**67**	**91**
HF8	**HF11**	1.08	*0.13*	0.32	*0.06*	0.06	*0.02*	**70**	**94**
HF8	**HF12**	1.03	*0.13*	0.31	*0.06*	0.07	*0.02*	**70**	**93**
HF8	**HF20**	1.09	*0.13*	0.33	*0.06*	0.07	*0.02*	**70**	**94**
HF8	**HF25**	1.06	*0.13*	0.32	*0.06*	0.07	*0.02*	**70**	**93**
HF15	**HF10**	1.10	*0.13*	0.32	*0.06*	0.08	*0.03*	**71**	**93**
HF15	**HF11**	1.00	0.11	0.30	0.06	0.07	0.02	**70**	**93**
HF15	**HF17**	1.10	0.12	0.34	0.06	0.07	0.02	**70**	**94**
HF15	**HF18**	1.11	0.12	0.31	0.05	0.08	0.02	**72**	**93**
HF15	**HF20**	1.01	0.11	0.31	0.06	0.08	0.02	**70**	**93**
HF15	**HF25**	0.98	0.11	0.30	0.05	0.08	0.02	**69**	**92**
HF16	**HF17**	1.06	0.11	0.29	0.05	0.06	0.02	**73**	**94**
HF23	**HF10**	1.10	*0.13*	0.32	*0.06*	0.06	0.03	**71**	**95**
HF23	**HF18**	1.11	0.13	0.31	0.05	0.07	0.02	**72**	**94**
HF23	**HF20**	1.01	0.12	0.31	0.06	0.06	0.02	**70**	**94**
HF23	**HF25**	0.98	0.12	0.30	0.05	0.06	0.02	**70**	**94**

Table 36. Lists the mean U-values from the 17 matching U-value pairs (from 13 locations on the floor) where the mean paired U-value was within the whole floor U-value error margins for each intervention. See Figure 63. for sensor locations (highlighted in red).

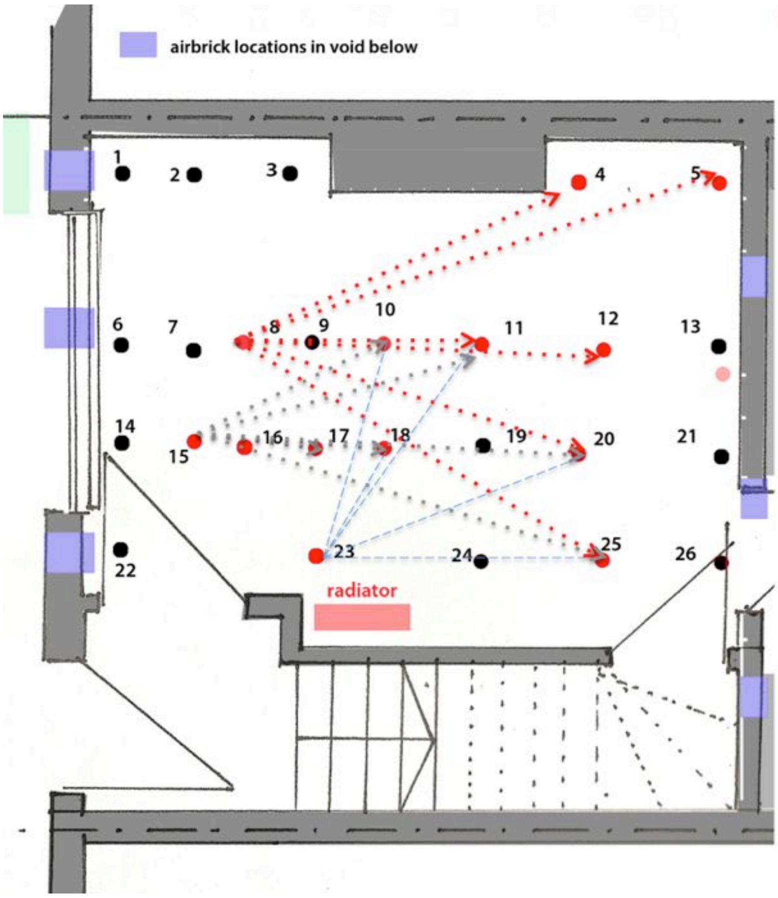


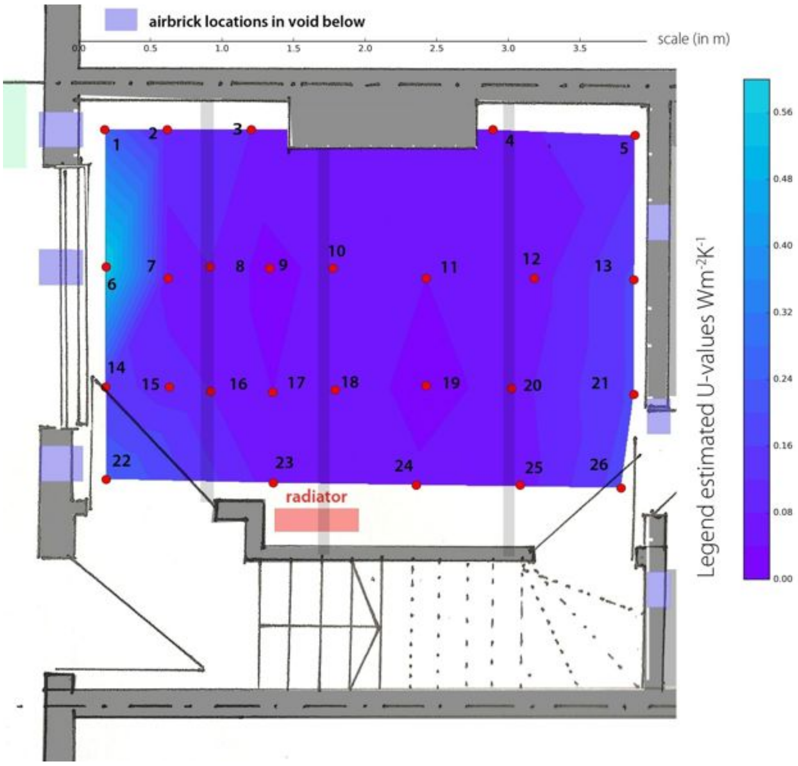
Figure 63. illustrates the 13 sensor locations in red which made up the 17 paired locations for which mean paired U-values were within the margins of error of the whole floor estimated U-value for all of floor interventions and the uninsulated floor. Note that middle of the floor locations are generally impractical for field work in occupied houses.

In summary, pairing of measurements was of limited use and reiterated the uncertainty around obtaining whole floor U-values from just a few measurements. No clear pairing patterns could be ascertained, though generally, no locations close to airbricks (<800mm) were included. The majority of pairs for this case study, included locations 8 or 15 in the perimeter zone (not aligned with airbricks below) or location 23 in the non-perimeter zone and were combined with either a location at the back of the floor or middle of the floor - see *Figure 63.* Middle of the floor locations are generally impractical for field work in occupied houses. More high-resolution monitoring needs to be undertaken to investigate if this remains elsewhere, particularly with different characteristics, including different number of airbricks, sleeper walls, *P/A* and house typologies.

6.4.3. Spread of point U-values and perimeter effect

As discussed in Section 5.3.1, (*Figure 51.),* the uninsulated floor U-values ranged between 0.54 ±0.09 $Wm^{-2}K^{-1}$ to 2.04 ±0.21 $Wm^{-2}K^{-1}$. For the bead-insulated floor, there was a significantly reduced spread of U-values in support of hypotheses H2a, ranging between 0.02 ±0.01 $Wm^{-2}K^{-1}$ (location 19) to 0.58 ±0.24 $Wm^{-2}K^{-1}$ (location 6, see *Figure 64.* and *Table 37.)*. For the woodfibre insulated floor (see *Figure 65. and Table 37.)* there was still a large spread of U-values: point U-values ranged between 0.18 ±0.04 $Wm^{-2}K^{-1}$ (location 4) to 1.89 ±0.22 $Wm^{-2}K^{-1}$ in location 6.

In both insulated floors, there were increased U_p-values in the perimeter zone in support of hypothesis (H2) but the perimeter effect, or the effect of the distance from the exposed wall, was significantly reduced once insulated, especially for the bead-insulated floor, when compared to the uninsulated floor. Despite observing reduced U_p-values in the perimeter zone, this perimeter effect was still considered statistically significant and hence supported hypothesis 2: Mann–Whitney W = 127, n1 = 9; n2 = 17, $P < 0.05$ (0.005, unpaired) for the bead insulated floor and Mann–Whitney W = 130, n1 = 9; n2 = 17, $P < 0.05$ (0.003, unpaired) for the woodfibre insulated floor. For the bead insulated floor the estimated mean of the perimeter U-values was 0.18 ±0.08 $Wm^{-2}K^{-1}$compared to 0.08 ±0.02 $Wm^{-2}K^{-1}$ for locations further away from the perimeter wall. For the woodfibre insulated floor the mean perimeter zone U-value was 0.64 ±0.11 $Wm^{-2}K^{-1}$ compared to 0.33±0.06 $Wm^{-2}K^{-1}$in the non-perimeter zone. In both cases, locations near the airbricks (sealed for the bead intervention) were generally outside the margins of error of other estimated point U-values and the pre/post U_p-values were also generally outside the estimated margins of error (see *Figure 66.* and *Figure 67.)*. For both floors, a significant drop in U_p-values seemed to occur >500mm away from the external wall.



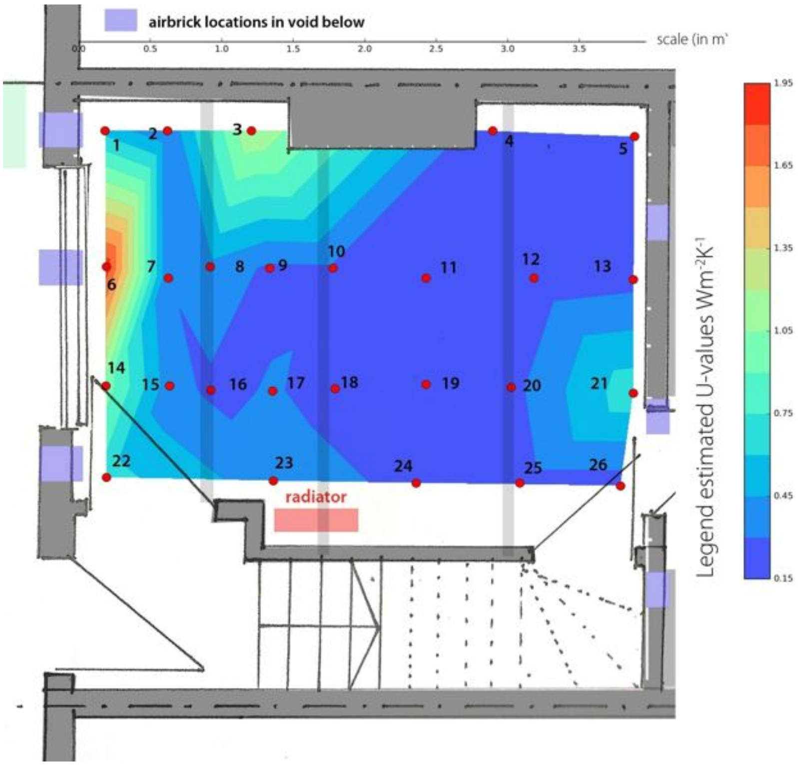


Figure 64. (top) Figure 65. (bottom) present for the bead insulated floor and the woodfibre insulated floor respectively, linearly interpolated U_p-values as a heat map between observed point U-value locations; point locations are marked with a red dot. Note that the maps only show interpolated values between points, no values between the walls and the points (hence the white zone). For estimated point U-values also see Table 37. Note: joist presence/thermal bridging not accounted for. Note that the colour legends are at the same scale.

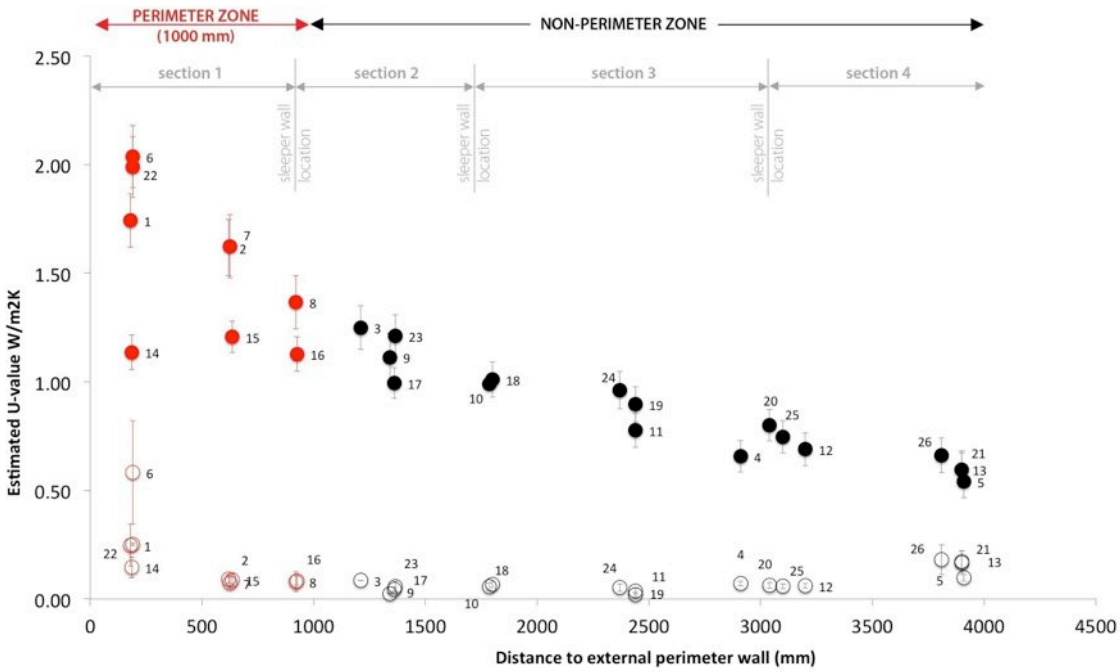


Figure 66. Plots the uninsulated U_p-values (solid data points) compared to bead-insulated U_p-values (outline data points) as a function of distance to the exposed wall. Red data points are located in the perimeter zone; black-data points in the non-perimeter zone. Error margins are as per Equation 50.; pre/post insulated point U-values are outside the estimated margins of error.

As expected, the bead insulated floor had an overall low estimated U-value, part of which is also derived from blocking up the airbricks, but a large quantity of insulating beads - around 3.6m^3 - was filled in the void, with 250mm insulation under the joists and 350 mm between joists. Nevertheless, from *Figure 64.* and *Figure 66.* it can be seen that there is still a perimeter effect and it can also be noted that there are slightly higher U_p-values in locations 5, 13, 21 and 26 along the kitchen/living room foundation wall. This might be caused by increased heat-transfer to the foundation wall and increased heat-flow to the uninsulated kitchen floor void - though this cannot be ascertained without further research. A similar trend was not observed for the neighbouring party wall foundation (locations 1 to 5), although this might be explained by the point locations being measured further away from the party wall compared to the kitchen foundation wall.

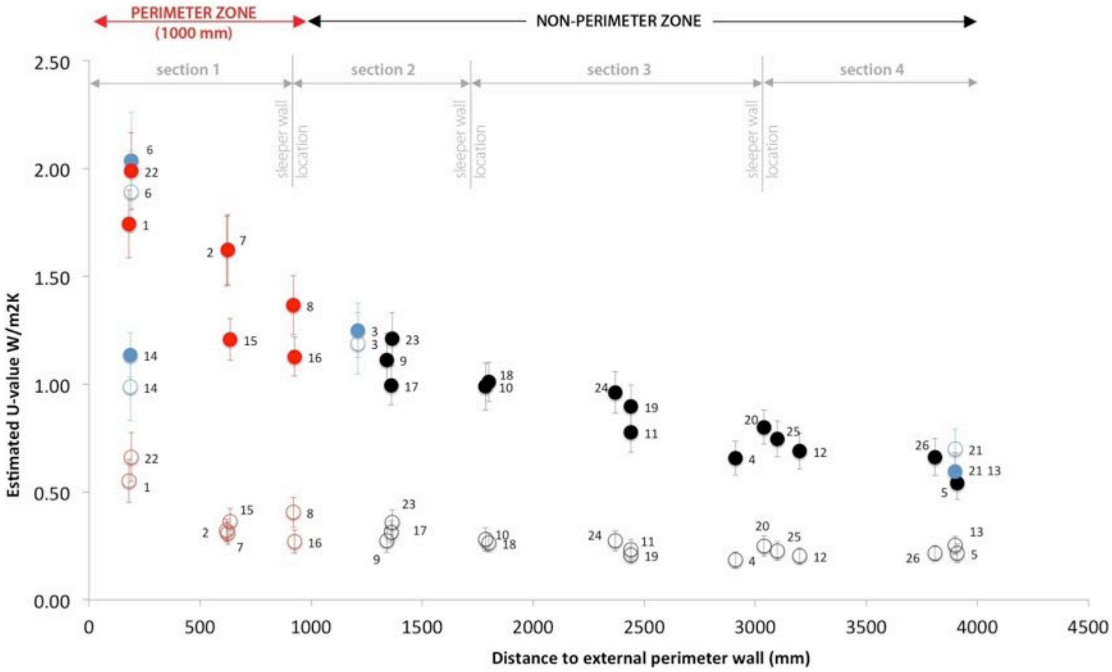


Figure 67. Plots the uninsulated U_p-values (solid data points) compared to woodfibre insulated U_p-values (outline data points) as a function of distance to the exposed wall. Red data points are located in the perimeter zone; black-data points in the non-perimeter zone. Error margins are as per Equation 53. Pre/post insulated U_p-values are generally outside the estimated margins of error, though U_p-values in locations 3, 6, 14 and 21 (in blue) are within the margins of errors, likely due to installation quality issues - see Section 6.4.3.1.

For the woodfibre insulated floor, a larger perimeter effect still exists, with a drop in U_p-values >500mm from the exposed wall. The more limited U_p-value reduction along the exposed edge might be explained by increased wind-speed post-insulation, however the exact quantity is unknown (see Section 6.3.2.2.). In addition, there were some insulation installation quality issues with only small reductions achieved in U_p-value in locations 3, 6, 14 and an increase in U_p-value was observed in location 21 (within the margins of error) - see final column *Table 37.* This is also illustrated by *Figure 67.* (blue data points) and *Figure 65.* and is further discussed in Section 6.4.3.1.

If relying on one point measurements only, *Table 37.* illustrates that depending on where the U_p-value was located, different conclusions could be drawn with regards to insulation efficacy; this could lead to over- or underestimation of insulation efficacy - see also previous Section 6.4.2.3. Finally, different environmental conditions affected pre/post interventions, though it is unclear how the above comparisons were affected - see Section 6.3.2.2.

Location	bead insulated floor- mean U (Wm^{-2}K^{-1})			% reduction from uninsulated	Woodfibre insulated floor- mean U (Wm^{-2}K^{-1})			% reduction from uninsulated
HF1	0.25	±	0.07	**86**	0.55	±	0.11	**68**
HF2	0.09	±	0.02	**94**	0.32	±	0.06	**80**
HF3	0.08	±	0.02	**93**	1.19	±	0.16	5
HF4	0.07	±	0.01	**89**	0.18	±	0.04	**72**
HF5	0.10	±	0.02	**82**	0.22	±	0.04	**60**
HF6	0.58	±	0.24	**71**	1.89	±	0.22	7
HF7	0.07	±	0.03	**95**	0.31	±	0.07	**81**
HF8	0.08	±	0.02	**94**	0.41	±	0.07	**70**
HF9	0.02	±	0.01	**98**	0.27	±	0.06	**75**
HF10	0.06	±	0.02	**94**	0.28	±	0.06	**72**
HF11	0.04	±	0.01	**95**	0.23	±	0.05	**70**
HF12	0.06	±	0.01	**91**	0.20	±	0.04	**71**
HF13	0.17	±	0.06	**72**	0.25	±	0.05	**58**
HF14	0.15	±	0.05	**87**	0.99	±	0.17	13
HF15	0.09	±	0.03	**93**	0.36	±	0.06	**70**
HF16	0.08	±	0.02	**93**	0.27	±	0.05	**76**
HF17	0.04	±	0.01	**95**	0.31	±	0.05	**68**
HF18	0.07	±	0.01	**93**	0.26	±	0.04	**74**
HF19	0.02	±	0.01	**98**	0.21	±	0.04	**77**
HF20	0.06	±	0.01	**92**	0.25	±	0.05	**69**
HF21	0.17	±	0.05	**71**	0.70	±	0.10	**-17**
HF22	0.25	±	0.10	**87**	0.66	±	0.18	**67**
HF23	0.06	±	0.03	**95**	0.36	±	0.06	**70**
HF24	0.05	±	0.02	**95**	0.27	±	0.05	**72**
HF25	0.06	±	0.01	**92**	0.23	±	0.04	**70**
HF26	0.18	±	0.07	**73**	0.22	±	0.04	**67**
HF_Joist_ 13b	0.18	±	0.05	**64**	0.51	±	0.08	**0**

Table 37. Presents the estimated point U-values with the total estimated uncertainty and percentage reduction after woodfibre insulation and bead-insulation compared to the pre-insulated floor. Only small U_p-value reductions were achieved in locations 3, 6, 14 and an increase in U_p-value was observed in location 21 - all highlighted in blue bold. This is likely due to installation quality issues - see Section 6.4.3.1. As expected, the joist U-value is similar pre/post intervention as this remained uninsulated in the woodfibre intervention, though is reduced after EPS bead-filling given the void was bead-filled under the observed joist location.

6.4.3.1. Impact of installation quality on intervention efficacy

Generally, U_p-value reductions after woodfibre insulation were between 58% to 80%, depending where pre/post measurements were taken (see *Table 37.)*. However, in some locations, thermal transmittance was still significant post-insulation, likely due to installation quality issues, as described below. Main installation issues included lack of tight-fitting of insulation with the underside of the floorboards (and nearby foundation walls) to *"prevent cold draughts getting behind the insulation"* (BRE, 2000), its importance also noted by EST (2005a). This was specifically pronounced in location 21 due to a bent floorboard which created a 15-20 mm gap between floorboard and insulation (see *Figure 68.b.)*. In addition, the breather membrane was cut in this location to retrieve void sensors, allowing a lead down into the void - this may not have been sufficiently taped. These issues might have created a thermal bypass, reducing the effective U-values - as illustrated in *Figure 67.* in Section 6.4.3. In Location 21 this lead to a 17% increased U_p-value after woodfibre insulation, though within the margins of measurement uncertainty - see *Figure 67*. Wingfield (2009) and Wingfield (2010) observed significant thermal bypass effects in masonry and timber-framed cavity walls.

Near the airbricks, insulation installation quality was also compromised by chamfering the insulation to allow for airflow through the airbrick in between joists as recommended by best-practice guidance- see *Figure 59.,* as discussed in Section 6.3.1. This reduced insulation quantity is likely to have affected all of the U_p-value estimates near the airbrick locations, likely leading to a more significant perimeter effect as illustrated in *Figure 65*. However, location 6 was particularly affected (see *Figure 68. a.)*: later investigation revealed that the chamfered insulation was slightly too short and did not fit tightly to the external wall. Additionally, the breather membrane did not fit well over and under the joists along the external perimeter wall (and kitchen foundation wall), as the edge floorboards were not taken up to avoid skirting damage. This meant that cold air might be able to flow up along the edges and create a thermal bypass, reducing the efficacy of the insulation along both walls. Such installation issues are likely to have contributed to an increased perimeter effect.

Finally, due to services in the void it was difficult to provide full insulation between joists in some locations; additionally, electrical power leads powering the airflow sensors in the void (which were absent in the bead insulated floor) were pulled through a large floorboard gap next to location 3; this affected insulation fit, likely leading to thermal bypass effects - see *Figure 68.(c.)*. and as visible on *Figure 65.*

It is unclear why location 14 had a reduced U_p-value reduction post-insulation installation, and might be due to any or a combination of the above issues, though further research would be required to confirm.

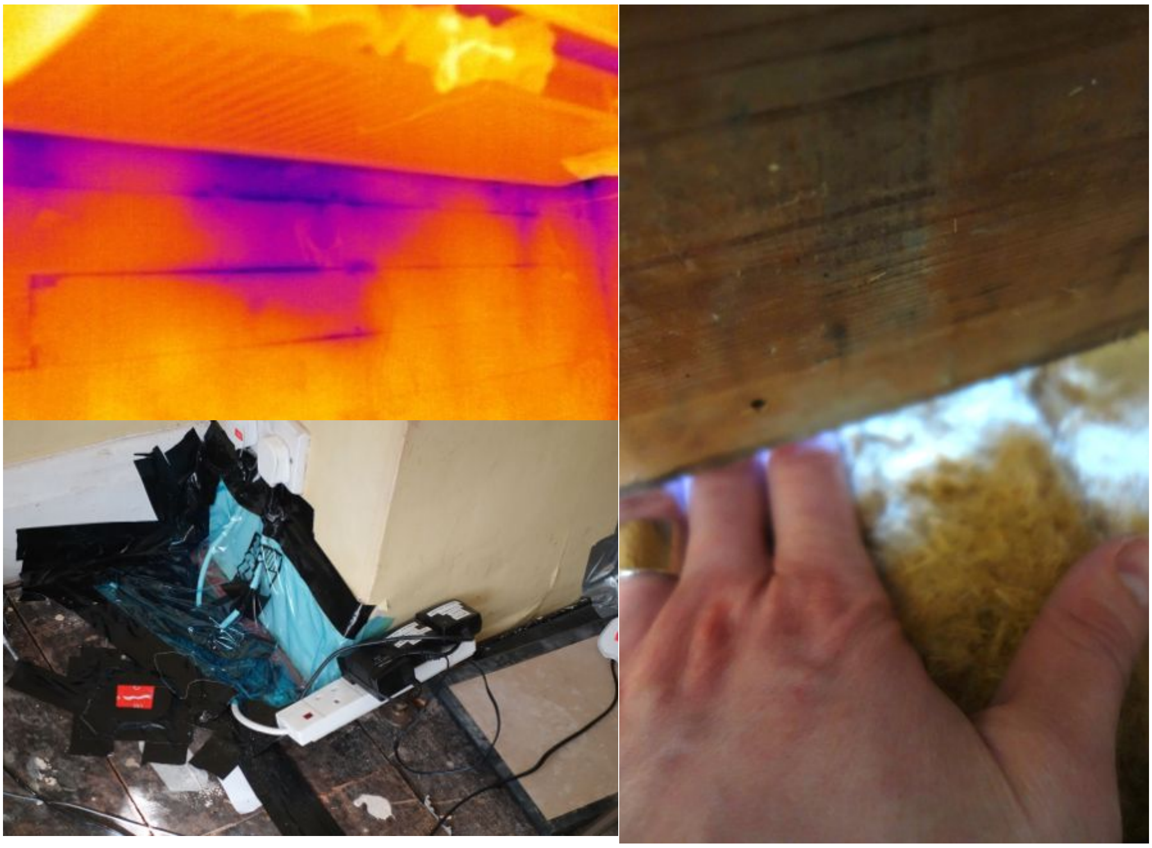


Figure 68. a., b. and c.: (a.) shows infrared image of woodfibre insulated floor with airbricks open and the ineffective fitting of insulation in location 6 along the perimeter; (b.) illustrates the gap underneath the floorboard and the top of the insulation in location 21 and (c.) shows the leads and airtight taping of the floorboard opening next to location 3.

While this field study might underestimate the efficacy of the insulation along the perimeter due to installation issues as described above, similar installation issues might occur during other installations. Different airbrick locations (i.e. in between or below joists) will lead to different thermal performance and further studies are required to investigate this effect.

6.4.4. Comparisons to modelled U-values

The same model inputs and assumptions were used for the insulated floors as for the uninsulated floor (Section 5.3.6.), aside from the addition of the insulation into the model and no airbrick openings for the EPS bead intervention; conductivities of the insulation materials are listed in *Table 38*.

The predicted U-value model estimate for the bead insulated floor was 0.08 $Wm^{-2} K^{-1}$ for all current models (and 0.09 $Wm^{-2} K^{-1}$ for the CIBSE-1986 model). The predicted U-value model estimate for the woodfibre insulated floor was between 0.22 and 0.23 $Wm^{-2} K^{-1}$ for the current models and 0.36 $Wm^{-2} K^{-1}$ for the CIBSE-1986 model- see *Table 38*. Model estimates were made both with and without joist presence to enable comparison with each other, though the in-situ measured whole floor U-values excluded joist adjustment.

Input assumptions (as per *Table 24., page 208*) unless stated otherwise; *assumed 1m/s wind-speed in brackets if different from default 5m/s assumption*	**Output ISO-13370**	**Output RdSAP**	**Output CIBSE**	**Output CIBSE 1986** *(assumed 1m/s wind-speed in brackets if different from default 5m/s assumption)*
All models based on survey input assumptions; U-value outputs, $Wm^{-2} K^{-1}$				
Uninsulated floor, excluding joist presence *(assumed 1m/s wind-speed in brackets)*	0.57 *(0.51)*	0.51 *(0.46)*	0.52 *(0.45)*	1.34 *(1.04)*
Uninsulated floor, including 12% joist presence	*0.57*	*0.51*	*0.51*	*1.31 (1.03)*
Bead insulated floor (with or without joist adjustments)[§§§] presence; beads Warmfill Silver; k= 0.033 $Wm^{-1}K^{-1}$ (BBA, 2014)	0.08	0.08	0.08	0.09
Woodfibre insulated floor - excluding joist presence; 100 mm Pavaflex k= 0.038 $Wm^{-1}K^{-1}$(Pavatex, 2013)	0.23 *(0.22)*	0.22 *(0.21)*	0.22 *(0.21)*	0.30 *(0.28)*
Woodfibre insulated floor- including 12% joist presence	*0.26 (0.25)*	*0.25 (0.24)*	*0.25 (0.23)*	*0.36 (0.33)*

Table 38. Different modelled outputs; based on site-survey and actual interventions taken place.; 5 m/s windspeed at 10 metres high; with no airbrick ventilation for the EPS bead insulated floor. U-values adjusted with joist presence are highlighted in grey italics.

[§§§] Differences whether including joists or not are only beyond the third decimal and make no significant difference to the estimated U-value rounded to the second decimal.

Comparing the ISO-13370 modelled uninsulated floor U-value (without joists) with the interventions, bead-insulating the floor would reduce the floor U-value by 86% and by 60% when woodfibre insulated. These are slightly underestimated improvements compared to the actual average measured reductions achieved: 92% (88% to 95%) for the bead insulated floor and 65% (54% to 75%) for the woodfibre insulated floor. This slight underestimation might be mostly due to the initial underestimation of the uninsulated floor (see 5.3.6.)

Figure 69. highlights that for this field study, the observed divergence between modelled and in-situ measured U-values reduced the better insulated the floor was. Cox-Smith (2008) also reported that a better insulated floor was closer to modelled thermal performance when investigating radiant foil insulation in newer floors in New Zealand. The increased convergence between in-situ measured and modelled U-values when better insulated might be due to the addition of increased insulation increasing the thermal resistance (which is fairly well known) and as the amount of insulation increases, it starts to dominate the total thermal resistance. In addition, for the bead-insulated floor, there might be fewer confounding (or assumed) variables: sealed airbricks removed ventilation both in in-situ measurements and the model. The bead insulated floor had a similar floor U-value whether in-situ measured (0.09 ±0.03 $Wm^{-2} K^{-1}$) or modelled (0.08 to 0.09 $Wm^{-2} K^{-1}$) for current and superseded models. Contrary to this, the uninsulated and woodfibre insulated modelled and in-situ measured U-values were outside the margins of error for the current models: the in-situ measured uninsulated floor U-value was about twice as high compared to current models (see also Section 5.3.6.), while for woodfibre insulation, the in-situ measured whole floor U-value estimate (0.36±0.07$Wm^{-2} K^{-1}$) was about a third higher than current model outputs. While the superseded CIBSE-1986 model appeared to overestimate the whole floor U-value by about 30% for the uninsulated floor, the modelled woodfibre insulated floor was within the margins of error of the in-situ measured floor U-value (underestimated by about 16%). Furthermore, if assuming 1 m/s wind-speed, the CIBSE-1986 model output of 1.04 $Wm^{-2} K^{-1}$ matched the in-situ measured whole floor U-value.

As for the all the modelled floors, it appears that the superseded CIBSE-1986 model outputs lead to smaller divergences with in-situ measured values, though further research is required to investigate if this would be the case for other in-situ measured case-studies. Similar issues apply about the conceptual differences between what is modelled and in-situ measured as discussed in Chapter 5.3.6. However, given the increased thermal resistance post-insulation, the impact of certain variables is likely to be proportionally smaller in the modelled U-values.

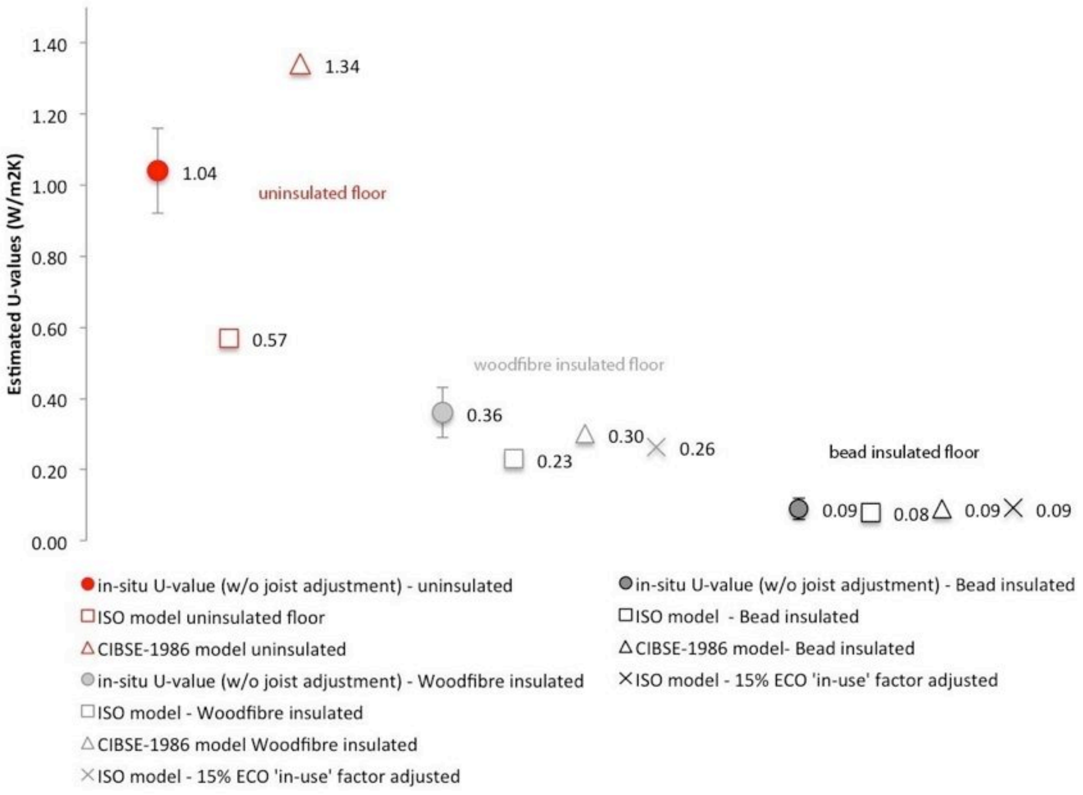


Figure 69. Compares the in-situ measured whole floor U-values (solid data points) with model estimates (outline data points) for all three interventions: uninsulated (red data points), wood fibre insulated (light grey data points) and bead insulated (dark grey data points). Error margins for in-situ measurements are based on Equation 49. for comparison to models. A +15% model adjustment after insulation (reflecting ECO 'in-use' factors) was also applied and indicates further alignment between models and in-situ estimated U-values (cross data points). All models are based on 5m/s wind-speed inputs as per SAP input assumptions (BRE, 2014b).

ISO-9869 (BSI, 2014) states that >20% differences between modelled and in-situ measured values are significant, which is the case here for the uninsulated and woodfibre insulated floors and current models. This divergence between modelled and measured might be due to any or a combination of the below:

- **Inaccurate model inputs:** while minimised by using data from a site survey where possible, there is still scope for wrong estimates and inputs, such as wind-speed and material conductivity assumptions; for example the brick foundation wall conductivity could be between 0.50 and 2.06 $Wm^{-1}K^{-1}$ (CIBSE, 2015); ground conductivity between 0.52 and 1.28 $Wm^{-1}K^{-1}$ (CIBSE, 2015). In the above models, default CIBSE (2015) or RdSAP assumptions were used, but the brief sensitivity analysis undertaken in Chapter 4.4.3.1. highlighted the impact of input variables on outputs.

- **Installation quality issues are not reflected in the models:** for the woodfibre insulated floor, the models above took no account of the chamfering of insulation near airbrick locations. While no in-situ point measurements were directly above these areas, this might have affected nearby perimeter locations - as discussed in Section 6.4.3. Adjusting models for installation quality issues can only be undertaken due to in-situ measurement and researcher's presence at insulation installation; for the field study only small adjustments to the models were made - see further below. Finally, the presence of service pipes and reduced insulation fit were excluded from in-situ measurements in this study (though might have affected nearby measurement locations) and are also excluded in models: generally perfect insulation fit is assumed, but this might be difficult to achieve in reality as discussed in Section 6.4.3.
- **Measured results might not be directly comparable to modelled results:** As discussed in Chapter 5.3.6., there are some conceptual differences between modelled and in-situ measured floor U-values: for instance inhomogenous room temperatures, short-term thermal mass effects and dynamic external conditions occur in reality while floor U-value models assume annual steady-state heat-flow as a proxy for seasonal heat-transfer. Furthermore, floor U-value models exclude linear floor/wall thermal bridge junctions; but in-situ measurements might have been affected by such junctions. Likewise, surface thermal resistances might be affected by airbrick airflow but this is excluded from models. Measuring conditions (internal and environmental conditions), assumptions and analysis methods also affect in-situ measurements as discussed elsewhere. It remains unclear however what the individual or combined impact is of these variables on the modelled outputs and how this affects comparison with in-situ measurements- further research is required.

Including actual installation quality issues in the model

Allowing for localised chamfered insulation installation in locations 1, 6 and 22 and a 10% air-gap correction factor (both as per ISO-9646 (BSI, 2007)), lead to slightly increased U-values: 0.25 $Wm^{-2}K^{-1}$ for the ISO-13370 model and 0.33 $Wm^{-2}K^{-1}$ for the superseded CIBSE-1986 model, slightly closer to the in-situ measured value of $0.36 \pm 0.07 Wm^{-2}K^{-1}$. The air-gap correction was only possible from in-situ observations, though it is still unclear if this also affected other locations than those observed - hence assumption of 10% occurrence was assumed. At present, ECO-policy uses a 15% 'in-use' factor for floor insulation for ECO-funded insulation installations (DECC, 2012) but it is unknown if this reflects different floor characteristics and installation quality. *Figure 69.* indicates further alignment of insulated floor U-value models adjusted with +15% to in-situ estimated U-values.

6.4.5. Other in-situ studies and U-value reductions from insulation

Only few in-situ measurements exist for insulated floors and for pre/post floor insulation studies. Direct comparison between floor insulation studies is challenging given previously noted different variables and - in the case of insulated floors - different insulation materials, insulation depth and material conductivities. Harris (1997) reported around 50% floor U-value reduction in a test cell after introduction of 30mm EPS insulation (with similar thermal conductivity as woodfibre insulation). This is a significant U-value reduction given the small depth of insulation, however due to the test-cell nature, comparison with in-situ field study results are difficult.

Currie (2013) reported a 71% point U-value reduction (from 2.4 $Wm^{-2}K^{-1}$ to 0.70 $Wm^{-2}K^{-1}$) after 80 mm woodfibre insulation installation in a detached cottage in Scotland. This is a slightly better improvement than the mean 65% reduction observed in this field study after 100mm woodfibre insulation installation, though within the experimental error estimate of reductions between 54% to 75% for the field study. The field study reduction is based on the whole floor U-value reduction of 26 points pre/post insulation; while the Currie (2013) study was based on observation of one point measurement located in the exposed perimeter zone (and unknown how close to airbricks). Given the initial high point U-value of 2.4 $Wm^{-2}K^{-1}$ in the Currie (2013) perimeter monitoring study means that the introduction of a large thermal resistance (i.e. the insulation) is likely to lead to a greater proportional U_p-value reduction in the perimeter compared to non-perimeter locations.[****] However this was not observed in the woodfibre intervention study here due to installation quality issues (see Section 6.4.3.1.). This again reiterates that estimating floor U-value reductions from one point measurement might over or under-estimate the insulation efficacy of the whole floor, depending on measurement locations and installation quality issues - see also Section 6.4.2.3.

[****] For example for the bead-insulated floor, largest U-value reductions were observed in the perimeter floor zone, with exception of locations nearest to airbricks and directly adjacent to the external wall - see *Table 37*.

6.4.6. Comparison to Building regulation recommendations

As discussed in Chapter 2.6., Building Regulations Part L1B recommend maximum design floor U-values of 0.25 $Wm^{-2}K^{-1}$ with a maximum allowable design U-value of 0.70 $Wm^{-2}K^{-1}$ for exceptions to listed buildings or where other regulatory relaxations apply (NBS, 2015, SBSA, 2015, Government, 2014, DFPNI, 2012).

The bead-filled floor void meets these regulatory requirements when both modelled (0.08 $Wm^{-2}K^{-1}$) and measured in-situ (0.09 ±0.03 $Wm^{-2}K^{-1}$); however it is unclear whether it would meet Building Regulations Part C (NBS, 2013), which stipulates a ventilated floor void.[††††]

Part L1B (NBS, 2010) recommends that to obtain a ground floor U-value of 0.25 $Wm^{-2}K^{-1}$ for a floor with *P/A* of 0.3, 97mm to 107mm insulation with thermal conductivity of 0.035 to 0.040 $Wm^{-1}K^{-1}$ between the joists is required[‡‡‡‡]. This specification is similar to the woodfibre insulated study and the U-values modelled with current models, which all met the building regulations upgrade requirements (see *Table 39.)*. However the superseded CIBSE-1986 model output does not meet the Part L1B U-value recommendation and when adjusting for joist presence, the ISO-13370 model also exceeds the recommendations. Further adjusting the modelled values with the +15% 'in-use' factor further increases modelled values, exceeding the recommended values.

Furthermore, the woodfibre insulated in-situ measured whole floor U-value fails to meet the building regulation requirement by about 30%. Without the perimeter airbricks in between the joists, greater in-situ heat-flow reductions might have been achieved, though it is unclear if this would have brought in-situ measured closer to modelled values and regulatory requirements. The presence of services and installation quality issues associated with airbrick locations and ill-fitting floorboards are excluded from models yet are likely to be practical issues present in other dwellings, preventing 'perfect insulation' installation. This raises questions about the practicalities of achieving the Building Regulations recommended design floor U-values of 0.18 to 0.25 $Wm^{-2}K^{-1}$, depending in which UK region.

†††† Shaftesbury Park Terrace which implemented EPS void-filling and permanently sealed airbricks was approved by local building control (Baeli, 2013, TSB, 2011).

‡‡‡‡ No information is provided with regards to ventilation area assumptions; 12% joist presence is assumed.

U-values	England ($Wm^{-2}K^{-1}$)	Wales ($Wm^{-2}K^{-1}$)	Northern Ireland ($Wm^{-2}K^{-1}$)	Scotland ($Wm^{-2}K^{-1}$)
Building Regulations **Floor - Upgrade**	0.25	0.18	0.18	0.18
Building Regulations **Floor - New buildings**	0.25[§§§§]	0.18	0.25	0.18
Model 100 mm wood fibre insulated (excl, 12% joist presence)	0.22 to 0.23 $Wm^{-2}K^{-1}$(current models); with ±15% 'in-use' adjustment: 0.25 to 0.26 $Wm^{-2}K^{-1}$ 0.30 $Wm^{-2}K^{-1}$ (old CIBSE-1986 model) - see *Table 38*.			
Actual in-situ measured 100 mm wood fibre insulated	0.36 ±0.07 $Wm^{-2}K^{-1}$ - excluding 12% joist presence 0.40 ±0.07 $Wm^{-2}K^{-1}$ - including 12% joist presence			
Model bead insulated	0.08 to 0.09 $Wm^{-2}K^{-1}$ - see *Table 38*.			
In-situ measured bead insulated	0.09 ±0.03 $Wm^{-2}K^{-1}$			
Uninsulated floor -model	0.51-0.57 $Wm^{-2}K^{-1}$ (current models) 1.34 $Wm^{-2}K^{-1}$ (old CIBSE-1986 model); 1.04 $Wm^{-2}K^{-1}$ with 1m/s wind-speed assumption			
Uninsulated floor -in-situ measured	1.04 ±0.12 $Wm^{-2}K^{-1}$			

Table 39. Limiting design U-values in the UK regions according to the regional building regulations for ground floors compared to modelled and in-situ measured floor U-values when woodfibre insulated (100mm in between joists) and bead insulated.

[§§§§] For extensions to existing dwellings, the requirement in Part L1A is 0.22 Wm^2K^{-1}.

Furthermore, joist depth limitations often apply and airbrick locations will limit the depth of insulation that can be fitted. In the field study, the 100mm available joist depth also limited the insulation that could be installed practically and without blocking the airbricks along the perimeter. While materials with lower conductivity might be suitable, they might not be as recommended by English Heritage for suspended floors (see *Appendix 2.B.*). Part L1B does allow for exemptions to meet the improved U-value of 0.25 $Wm^{-2}K^{-1}$where it "*is not technically, functionally or economically feasible*" and instead to upgrade to "*the best standard that is technically and functionally feasible and delivers a simple payback period of 15 years or less*" (NBS, 2015).

Additionally, the RdSAP model, used for existing building upgrades, assumes that 150 mm insulation will be installed between the joists (BRE, 2012); which would not be possible in the field study and in other cases for reasons mentioned above. BRE (2012) recommends floor insulation where <50 mm insulation is present and where U-values are > 0.50 $Wm^{-2}K^{-1}$, while the building regulations state that *"where the existing floor U-value is greater than 0.70* $Wm^{-2}K^{-1}$*, then the addition of insulation is likely to be cost-effective"* (NBS, 2015). While the in-situ measured floor U-value was found to be significantly higher than both these thresholds recommended for insulation, the modelled U-values of the existing uninsulated floor (0.51 to 0.57 $Wm^{-2}K^{-1}$, current models, see Chapter 5.3.6.) are around the 0.50 $Wm^{-2}K^{-1}$ RdSAP threshold for insulation but significantly below the 0.70 $Wm^{-2}K^{-1}$ recommended regulatory threshold. In the case of the field study, this has implications for retrofit decision making and regulatory requirements: according to models it may not be cost-effective to upgrade the floor and may lead to regulatory exemptions, possibly leaving the floor uninsulated. Yet in reality the floor U-value may be significantly greater than predicted by the current models, and hence lead to greater cost-effectiveness to insulate. For example,, for the field study, the yearly estimated energy cost associated with uninsulated floors is just £28 according to the modelled U-value but £51 compared to the in-situ measured value. As such, a simplified payback model indicates that the payback of insulating floors is very long (between 15 and 117 years), especially when based on modelled U-values*. Depending on insulation costs and according to the modelled U-values, a payback of 42 to 117 years is estimated when woodfibre insulated compared to 21 to 58 years when based on actual in-situ measured values and reductions. The payback of the bead-insulated floor might be as low as 15 years based on in-situ measurements, while double that based on predictive models. This also indicates that further research into actual space-heating energy use associated with floor heat loss and more cost-efficient floor insulation methods are needed.

***** Estimates based on London Heating Degree Days and EH (2013) floor insulation cost estimates of £25/m^2 to £70/m^2; 4 p/kWh gas-heating cost (Npower, July 2016), excluding standing charges. Impact of draughts and any energy compensating behaviour associated with floor heat loss, financial incentives (ECO-funding) or DIY options are also excluded.

6.4.7. Proportional heat-flow

The proportion of heat-transfer through uninsulated floors is considered small compared to uninsulated walls and roofs (NBS, 2015), and depends on dwelling typology (terraced house/semi-detached house etc.) and the overall fabric efficiencies, as discussed in Chapter 1.2. This might explain why floor insulation has not been of much importance in energy policies, in favour of wall and loft improvements first.

A simplified dwelling fabric heat-transfer model (see *Equation 55.*) was used to estimate fabric heat-transfer (W/K) by assigning U-values to the exposed surface areas of the field case study dwelling, in accordance with SBSA (2010) and McMullan (2002). For simplification purposes, infiltration heat-losses - while an important aspect of overall building heat loss - were excluded in this simplified exercise. Fabric U-values from CIBSE Guide A were used alongside the ISO-13370 modelled floor U-value of 0.57 $Wm^{-2}K^{-1}$ for the uninsulated floor, while a literature average value of 0.77 $Wm^{-2}K^{-1}$ was used for a semi-detached house floor due to absence of in-situ U-values for a semi-detached field-study. Fabric areas were based on a survey of the field case study as described in Chapter 5.2.1, *Table 24.* To represent a semi-detached dwelling, its party wall was taken to be a gable wall with a small window added, as per house design in the field study vicinity. Note that for this simplified exercise it was assumed that there was no heat transfer between party walls or party floors (for apartments); the apartment has a party floor as its 'roof'.

$\sum_{i=1}^{n} U_i A_i$ - *Equation 55.* Is the total estimated heat loss (W/K) per degree K, where n is the number of fabric elements (i) in the building; U is the fabric U-value ($Wm^{-2}K^{-1}$) of element i; and A is the surface area (m^2) of element i.

Based on this simplified model and assumed inputs, the proportional heat-transfer from the uninsulated floor was estimated to be between 10% to 13% for semi-detached and terraced houses and 24% for ground floor apartments (assuming uninsulated dwelling fabric, apart from 150 mm loft insulation and double glazed windows). Taking into account the field study's in-situ measured whole floor U-value of 1.04 $Wm^{-2}K^{-1}$ (Chapter 5.3.2.) increased the proportional heat-transfer from the floor to 25% for the terraced house and 39% for the ground floor apartment[*****] - significantly greater than is assumed at present.

[*****] Note: no semi-detached house in-situ floor U-values were assumed here given that only a terraced house was measured in the thesis. For the apartment, the same ground floor area and in-situ U-value was assumed as the ground floor area would remain the same.

When all elements, apart from the ground floor are upgraded to current building regulation design values, the proportional floor heat loss generally becomes the largest heat loss contributor of the opaque fabric elements: between ~29% and 45% depending on dwelling typology - see *Figure 70.* While the absolute floor heat loss may remain the same, leaving the floor uninsulated might create a barrier to achieving thermal comfort and is a missed opportunities for further energy and carbon emission reductions. Similarly, when taking into account the field study's in-situ measured floor U-value, proportional floor heat loss could be as much as 44% for a terraced house and 60% for a ground floor apartment - see *Figure 71*. When additionally insulating the floor to regulatory design values of 0.25 $Wm^{-2}K^{-1}$, the proportional floor heat loss reduced to between 16% and 26%; however this increased to 21% for the terraced field study and to 34% for the ground floor apartment when assuming the in-situ measured woodfibre insulated whole floor U-value of 0.36 ±0.07 $Wm^{-2}K^{-1}$as measured in this study - see *Figure 72*.

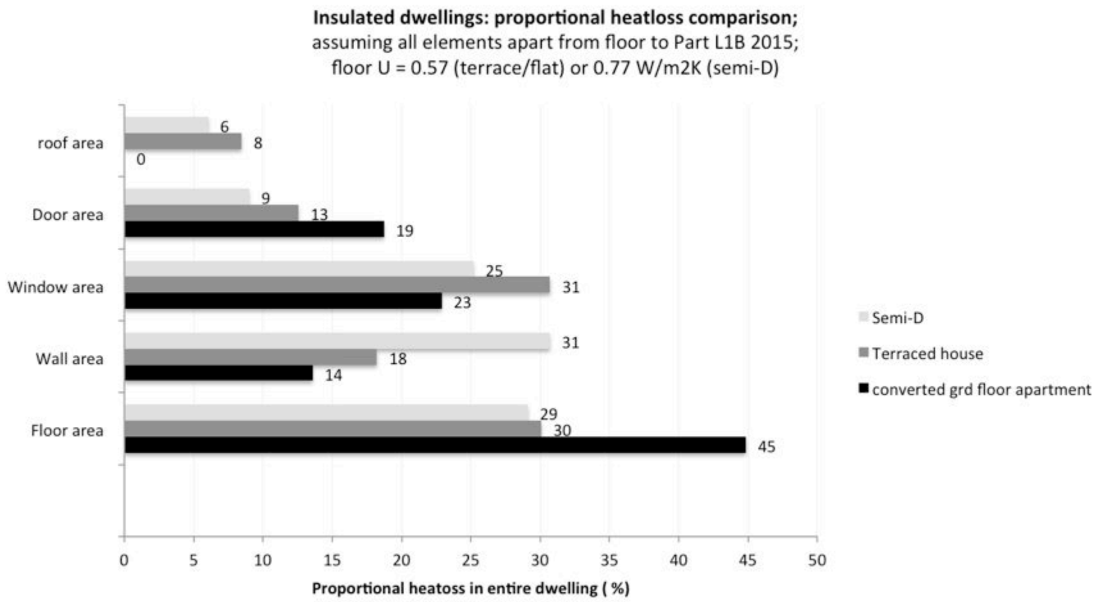


Figure 70. Proportional heat loss comparison of different dwelling typologies in a dwelling where all elements are upgraded to Part L1B 2015, but the floor is left uninsulated. The black bars are for ground floor apartments; dark grey for terraced and light grey for semi-detached dwellings.

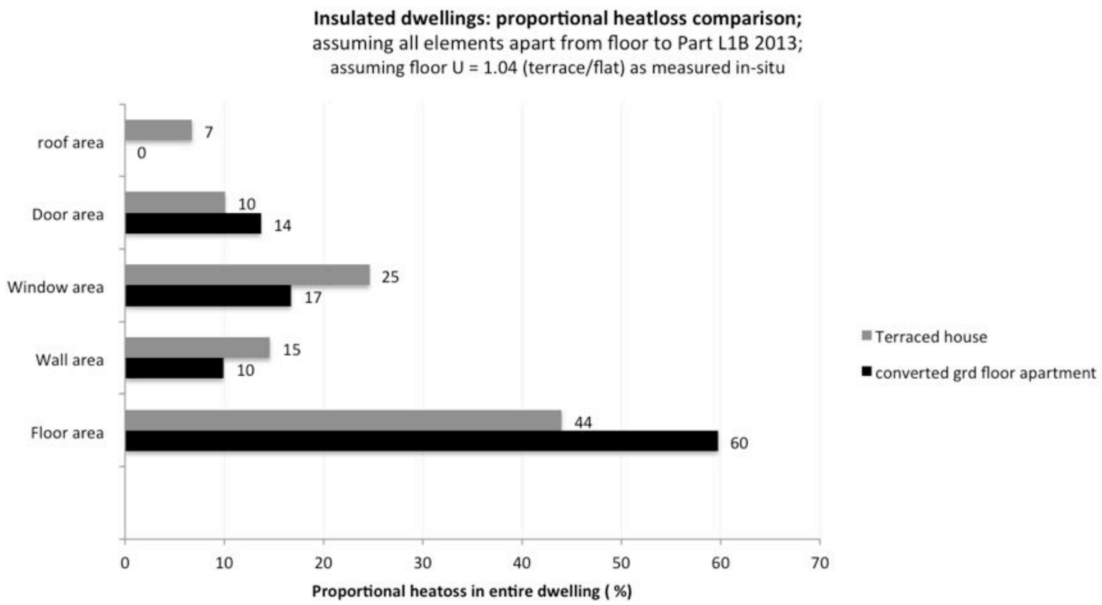


Figure 71. Proportional heat loss comparison of terraced house with ground floor flat where all elements are upgraded to Part L1B 2015, with floor in-situ performance of 1.04 $Wm^{-2}K^{-1}$as per Chapter 5. 3.2. Semi-detached dwelling excluded as no in-situ data available.

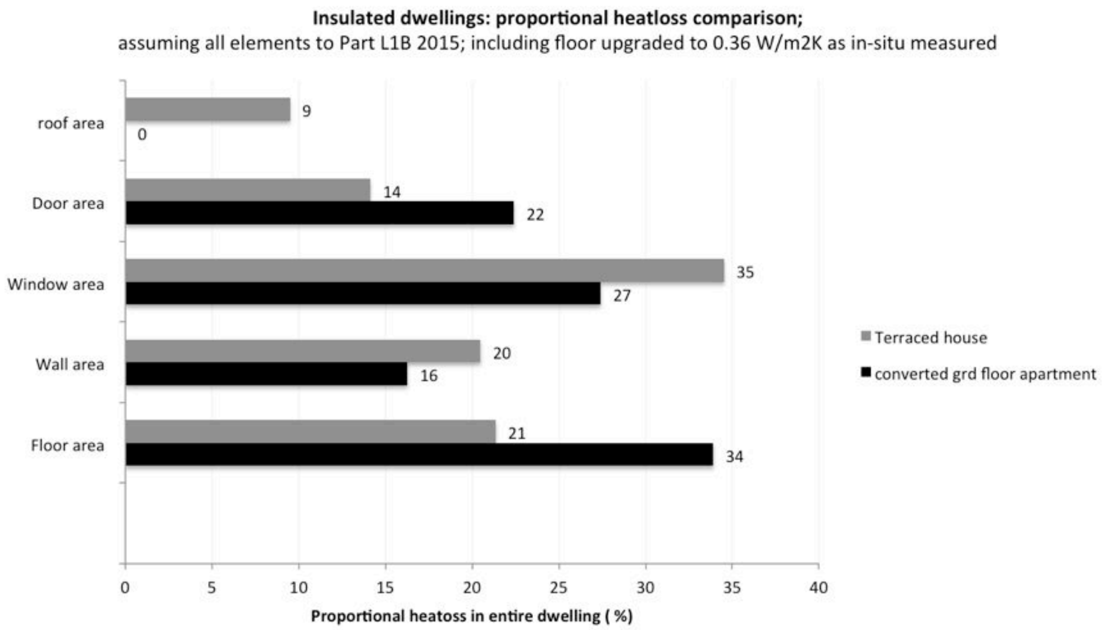


Figure 72. Proportional heat-loss comparison of terraced house with ground floor flat where all elements are upgraded to Part L1B 2015, and the floor is assumed to be insulated according to the whole floor estimated U-value of the field case when woodfibre insulated (i.e. 0.36±0.07 $Wm^{-2}K^{-1}$). Semi-detached dwelling excluded as no in-situ data available.

6.5. Thermal comfort and airtightness implications of insulating floors

Positive consequences of insulating floors might be increased airtightness from intervention measures and increased thermal comfort - both are discussed in this section, with preliminary and limited evidence presented from data collected. Given that the field study was unoccupied, no occupant thermal comfort study could be undertaken hence testing hypothesis 6 (*"H6. Post-insulation it will be observed that thermal comfort is improved"*) was limited. Instead, room air temperature measurements in the room pre- and post intervention were compared with theoretical comfort thresholds as set out in ASHRAE (2013) and BSI (2006). This approach was additionally limited by the constraints of the comfort theories as discussed in Chapter 2.5.

All temperatures referred to here are during heating-on periods, unless stated otherwise. It was observed that mean room air temperatures (at 1.1m height) were just below 20°C and below the CIBSE (2015) thresholds for comfort; this was expected given that heating set-points were below these thresholds, as discussed in Section 6.3.3. and Chapter 5.2.3.3. Mean uninsulated surface floor temperatures were just below 16°C±0.1°C during occupied hours; while 17.5°C±0.1°C for the insulated floors. *Table 40.* illustrates that all mean floor surface temperatures in the middle of the floor were significantly below the 19°C thermal comfort threshold in all cases for 100% of the occupied time, with exception of the woodfibre insulated floor: for 99% and 43% of the monitored time was found to have surface temperatures ≤19°C for open and sealed airbricks respectively. It is unlikely this was due to the woodfibre intervention alone: monitoring took place in late winter and this monitoring period was subject to a warmer external environment - see Section 6.3.2.2. With sealed airbricks, the highest mean floor surface temperature of 18.8°C was also recorded for this floor. With open airbricks, the 3°C head-feet (seated and standing) threshold was exceeded for the majority of the time (> 78%) for the uninsulated floor - see *Table 40.* Similar findings were also reported by Gauthier (2014) for living areas with unsealed airbricks and uninsulated floors, where 5 of 10 observed dwellings exceeded the 3°C threshold for about 50% of the time (but not so for bedrooms).

Thermal comfort variables or thresholds	All open airbricks, apart from bead insulated			Sealed airbricks	
	Heated/occupied hours only. Measured in middle of living room.				
	uninsulated floor	bead insulated floor	woodfibre insulated floor	uninsulated floor	woodfibre insulated floor
Mean floor surface temperature (middle floor, location 10)	15.7±0.1ºC	17.5±0.1ºC	17.5±0.1ºC	16.8±0.1ºC	18.8±0.1ºC
% of time floor surface temperatures < 19ºC	100%	100%	99%	100%	43%
Mean temperature 1.1m high	19.6±0.1ºC	19.7±0.1ºC	19.7±0.1ºC	19.7±0.1ºC	20.2±0.1ºC
Mean temperature difference feet and head (seated) in ªC (0.1-1.1m)[†††††]	3.7±0.14ºC	3.2±0.14ºC	3.2±0.14ºC	3.7±0.14ºC	2.1±0.14ºC
Average temp difference feet and head (standing) in ªC (0.1-1.7m)[‡‡‡‡‡]	4.6±0.14ºC	4.1±0.14ºC	4±0.14ºC	4.7±0.14ºC	2.8±0.14ºC
% of time ≥3ºC seated	78%	65%	59%	77%	8%
% of time ≥3ºC standing	92%	89%	82%	100%	26%
External temperatures (during occupied hours)	5.9	5.7	7.6	7.3	12.1

Table 40. presents the mean surface temperatures in the middle of the floor, the ΔT between feet and head when seated (0.1m-1.1m) and standing (0.1m-1.7m) and % of time that these thresholds were ≥3ºC threshold.

[†††††] Error margin is estimated from the quadratic sum of the two individual instrument errors of each measurand.
[‡‡‡‡‡] idem

Impact of floor insulation on thermal comfort

Hypothesis 6 (*"Post-insulation it will be observed that thermal comfort is improved"*) was supported by the preliminary data collected, although the differences appeared small and further research is required to investigate the full impact of floor insulation. As expected, floor surface temperatures in the middle and non-perimeter zone of the floor were generally higher than those in the externally exposed perimeter zone and near airbricks. This is illustrated by *Figure 73.*, indicating mean surface temperatures between 13.2±0.1ºC and 19.2±0.1ºC, depending on intervention and location on the floor. The average floor surface temperature of the uninsulated floor in the middle of the room was 1.8ºC ±0.14ºC lower than when insulated (see *Table 40.)* for both interventions. Depending on location on the floor and insulation intervention[§§§§§], increased floor surface temperatures were observed between 0.5ºC±0.14ºC and 2.9ºC±0.14ºC- see *Figure 73*. Mann–Whitney U tests (n1 = n2 = 26, P <0.05 (0.00000003), paired) confirmed that these changes in floor surface temperatures pre/post insulation were statistically significant for both insulation interventions. However, the floor surface temperatures were still significantly below the 19ºC temperature threshold (predicted 10% PPD after ASHRAE (2013) and BSI (2006)); though the better the floor was insulated, the fewer locations below 15ºC surface temperatures (predicted 20% PPD) - see *Figure 73*. Mean floor surface temperatures were significantly lower (0.5 to 3ºC) during unheated periods compared to when space heated, with 1.3±0.14ºC difference on average.

As noted prior, monitoring of the woodfibre floor was undertaken later in the heating season which was likely to have affected these results and this might explain the comparatively smaller thermal comfort impacts from the bead insulated floor, which was a better insulated floor and with three airbricks closed.

[§§§§§] For a visual spread of surface temperatures across the floor, see Appendix 6.E. Note that these include both heating-on and heating-off periods.

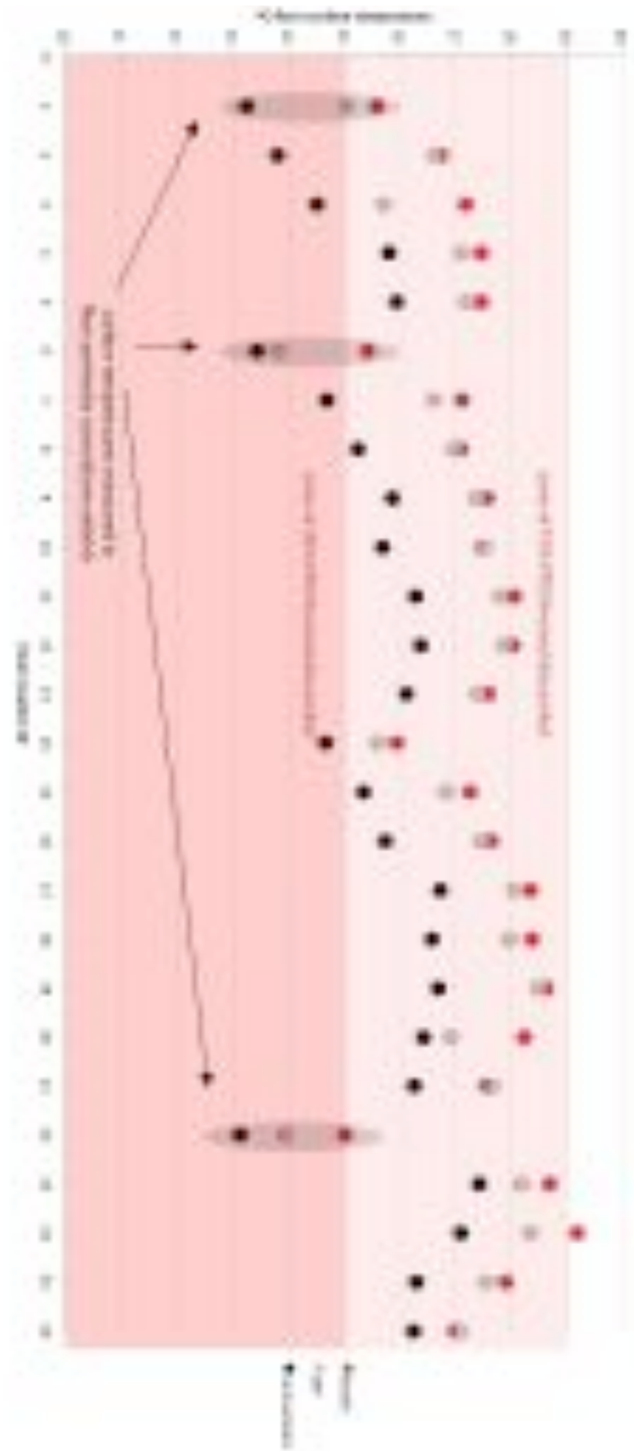


Figure 73. Mean floor surface temperatures during heating-on periods when uninsulated (black data points), or wood fibre insulated (WF, grey data points), (both with open airbricks) or when bead filled (red data points, sealed airbricks). The light pink shaded zone indicates the expected 10% PPD thermal discomfort zone with floor surface temperatures <19ºC and the darker pink zone indicates 20% PPD with floor surface temperatures <15ºC. Margins of instrument error of ±0.1 ºC are not visible on this graph. PPD after ASHRAE (2013) and BSI (2006). As expected, the better insulated the floor was, generally the higher the observed mean floor surface temperatures; the highest mean surface temperatures were observed for the bead-insulated floor (red data points) and the lowest for the uninsulated floor (black data points).

No significant differences were noted in mean air temperature (1.1m height) pre/post insulation. The insulated floors in this field study were not made airtight, which might have limited the impact on warmer internal air temperatures - see Section 6.5.1. It should also be noted that given the different external environmental conditions in which the intervention studies took place, these changes (or lack of changes) may have been caused by different environmental conditions rather than associated with the interventions - further research is required. This might also (partially) explain why the field study did not replicate other research findings: Saint-Gobain (2014a) and Fitton (2014) reported a 1.5°C±0.50°C reduction in vertical temperature gradient (standing) after insulating the Salford EH in a separate floor study, though this also included making the floor airtight (Saint-Gobain, 2014a), see Section 6.5.1. Instead, in the field study only a small effect of reduction in vertical temperature gradient was observed post-insulation: for the seated average temperature gradient, there was a reduction of just 0.5°C±0.1°C for each of the interventions compared to when uninsulated. A standing average temperature gradient of 4.6°C±0.14°C was observed for the uninsulated floor and this was reduced by just 0.5°C±0.1°C and 0.6°C±0.1°C when bead or woodfibre insulated respectively. Post-insulation, the head-feet temperature difference thresholds were still above the 3°C comfort threshold for the majority of time, though slightly reduced post-insulation - see *Table 40*.

Impact of sealing the airbricks (i.e. reducing floor void ventilation) on thermal comfort

From *Table 40*. it can be noted that the maximum 3°C temperature difference threshold between head-feet when standing was not met for the majority of the time with either airbricks open or closed, apart from the woodfibre insulated floor with sealed airbricks, though this was monitored later in the winter season with significantly warmer external temperatures during occupied hours. As such no robust comparisons between woodfibre pre/post sealing of airbricks could be made for thermal comfort. While the sealing of airbricks increased the floor surface temperature of the uninsulated floor (though still below the theoretical thermal comfort thresholds), the warmer external temperatures during occupied hours were a confounding factor. Furthermore, changes in room air temperatures and to the head-feet temperature differences were marginal with sealed airbricks and within instrument error margins. Hence the effect of closing the airbricks on theoretical thermal comfort thresholds remains inconclusive.

6.5.1. Airtightness after floor insulation

As discussed in Chapter 3.2.6., in-situ measured U-values exclude the heat loss from air leakage through floors (i.e. ingress of uncontrolled external and void air coming inside through gaps and cracks in the floor). McGrath (1996), Hartless (1994) and Basset (1988) suggest that airflow moves up through the floor to internal spaces rather than cross-ventilated from one floor void end to another.[******] Associated thermal comfort impacts might lead to compensating energy-use behaviour by occupants; for example, increasing air temperatures to offset draughts or discomfort from cold floor surface temperatures (Olesen, 1979, Rock, 2013). In addition, as discussed in Chapter 2.7., air infiltration through the floor void could also bring contaminants into indoor spaces, hence increasing airtightness of the floor may be important in terms of energy use, local thermal comfort sensation and health (Sherman).

Stephen's (1998) large scale study of 411 dwellings found that about half had suspended timber ground floors with air change rates of 16.5 ach^{-1} at 50Pa, as expected higher than the remaining solid ground floors with ~11.5 ach^{-1} at 50Pa. As anticipated, air leakage was found to be worse with standard square-edged floorboards compared to tongue and grooved boards, where most leakage occurs around service penetrations and wall/floor junctions (Stephen, 1998). For seven houses, the relative air leakage from suspended timber ground floors with bare floorboards was observed to be 3.5% to 25.4% of the total dwelling air leakage (Stephen, 1998) while Lilly (1988) found this to be on average 65% (based on one test-house with seven airbricks); different variables of the study houses (such as floor areas) make comparisons challenging.

For the field study, a limited air leakage study was conducted: dwelling air leakage was investigated by (a). measuring dwelling airtightness with the uninsulated floor; (b.) measuring dwelling airtightness post-insulation interventions and with sealed airbricks and (c.) estimating a relative improvement in airtightness after sealing the floor for the same field study dwelling with the Standard Assessment Procedure (SAP). No internal airflows or internal airflow velocity were measured in the case study house, limiting understanding of the impact of floor airtightness on thermal comfort. No separate floor air leakage was measured for reasons as discussed in Chapter 3.2.4.

[******] In this study, the living room and kitchen floor voids were isolated in any case - see Chapter 5.2.

6.5.1.1. SAP and airtightness assumptions

SAP and RdSAP (Reduced SAP) are used for the modelling of new or existing buildings and for building regulation compliance but could benefit from input refinement to more accurately predict actual fabric performance and energy use (May, 2012, Gentry, 2010, ZCH, 2014). (Rd)SAP make three simplified input assumptions about air leakage through the floor (BRE, 2014), assuming that floor infiltration depends on dwelling age bands with pre-1982 dwellings having 'unsealed' floors and more recent floor constructions are assumed to be 'sealed':

- 0.2 ach^{-1} for unsealed floors (pre-1982);
- 0.1 ach^{-1} for sealed floors (post-1982);
- and 0 ach^{-1} for solid ground floors.

It is unknown what the above assumptions are based on; floor air leakage is one of several variables assumed in the dwelling's infiltration heat loss (alongside infiltration through windows, entrance doors, chimneys and fans) and depends on dwelling exposure to winds and typical monthly average wind-speeds. Modelling the field study with an unsealed floor, SAP estimated a whole house ventilative heat loss (W/K) of about 20% more than if this were a solid ground floor. Just a 10% improvement was estimated from sealing the unsealed floor, though it is unclear what assumptions the 'sealing' of the floor are based on. In any case, this suggests only a limited benefit when making the floor airtight for this field-study, according to RdSAP.

6.5.1.2. Blower door tests: findings and discussion

Blower door tests were undertaken to investigate the impact of floor insulation and airbrick sealing on the overall dwelling airtightness, in accordance with ATTMA (2010) test standards and envelope area calculations.

It was hypothesised that installation of floor insulation would improve dwelling airtightness (Hypothesis 5a), as was reported by Saint-Gobain for the Salford Energy House, where reductions of 42% for floor insulation installation are reported (Saint-Gobain, 2014a, Saint-Gobain, 2014b); Banfill (2011) also reported similar results. In addition, by sealing airbricks, the air leakage from the airbricks might be estimated; however no tests were undertaken to estimate the proportional air leakage from the floor to the whole dwelling ventilation rate. This is because - as discussed in Chapter 3.2.4. - tracer gas techniques were not practical for mixing in floor void spaces (Edwards, 1990) and no pressurisation fans were available to (de)pressurise the floor void through the airbricks as undertaken by for example DeWitt (1994). Temporary sealing of the floor surface was not successful due to the effect of the blower door test on the temporary seals.

The average of the pressurisation and depressurisation tests are presented in *Table 41*., based on 7 pressurisation points for each (i.e. approximately 65Pa, 57Pa, 49Pa, 41Pa, 33Pa, 25Pa and 20Pa). According to ISO (2006) the typical uncertainty of air permeability tests in calm conditions (i.e. windspeed <0.45 m/s) is ±5 to ±10%, and can be as much as ±20% in windy conditions. BSI (2001) states higher uncertainties of less than ±15% in calm conditions and as much as ±40% in windy conditions, though typically between ±5 and ±10%. In this study, a ±10% measurement error was applied as generally the tests were conducted in calm conditions - see *Table 41*. Measurements were repeated on different days for the same intervention where possible; these were all within 0 to ±5% of one another and well within the above stated margins of error. For comparison purposes, results presented here are based on tests conducted with most similar external conditions as the other interventions, especially taking wind-speed into account. It is unknown when the UCL blower door test kit was last calibrated, which might have impacted on results - though its quantity is unknown.

Figure 74. Illustrates the author in the process of installing the blower door in the field study.

Based on the measurements, the uninsulated field study had an estimated air change rate of 14.2 ±1.42 ach^{-1}(see *Table 41*.), this is slightly better than Stephen's (1998) sample mean dwelling airtightness with suspended floors but - as expected - above the sample mean of the solid ground floor dwelling airtightness. However, *Table 41*. and *Figure 75*., highlight that for this field study, no significant differences were found between dwelling airtightness pre/post floor insulation. This means that hypothesis H5a (*"...insulation will also be observed to improve dwelling air tightness")* was not supported, suggesting that the insulation in itself had no significant effect on airtightness in itself for the field study. It also means that for this study, the RdSAP assumption of 10% improvement was overestimated but it was also unclear what this was based on.

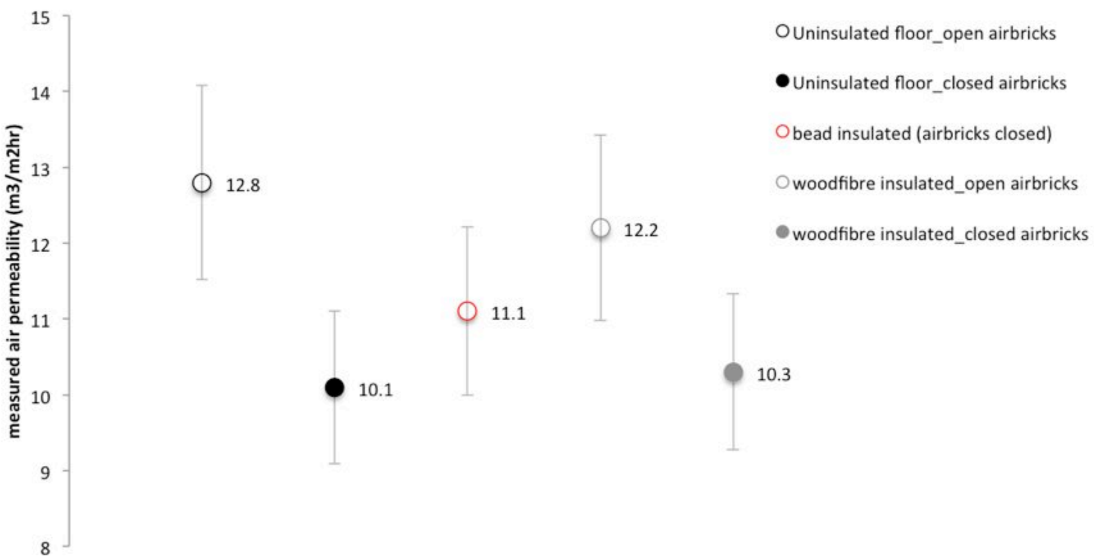


Figure 75. In-situ air leakage test results for all interventions and with airbricks open (outline data points) or sealed airbricks (solid data points) for the field case study; ±10% error margins.

Intervention	**when?**	**result** (m^3/m^2hr) at 50Pa	**result** (ach^{-1}) at 50Pa	**Average external wind speed** (m/s) at 2.8 metres high (back of house)	**% difference with uninsulated**
Open airbricks (unless bead insulated)					
uninsulated floor, bare floor boards	20.01.2014, 1.30pm	12.8 ±1.28	14.2 ±1.42	0.25 ±0.12 m/s	-
bead insulated (airbricks closed)	10.02.2014, 10 am	11.1 ±1.11	12.3 ±1.23	0.20±0.12 m/s	13
woodfibre insulated	01.03.2014, 1pm	12.2 ±1.22	13.6 ±1.36	0.49±0.12 m/s	4
Sealed airbricks					**% difference open/closed, with same intervention**
uninsulated floor, bare floor boards	20.01.2014, 2pm	10.1 ±1.01	11.2 ±1.12	0.25±0.12 m/s	21
woodfibre insulated	01.03.2014, 12.30pm	10.3 ±1.03	11.4 ±1.14	0.62±0.12 m/s	16

Table 41. Air leakage test results for each of the field study interventions, including opening and closing of the airbricks and % differences (final column).

Unlike the Saint-Gobain and Banfill (2011) study, just a 4% improvement in dwelling airtightness was observed after woodfibre insulation, though the airtightness effect might be under-estimated due to increased external wind-speed compared to the uninsulated floor. A 13% improvement for the bead filled floor was observed but was also within the margins of error - see *Figure 75*. The sealing of airbricks for the bead-intervention might be the likely explanation of the 13% improvement in dwelling airtightness, rather than resulting solely from the insulation intervention itself. This is because it was observed that airbrick sealing appeared effective in improving dwelling airtightness: dwelling air leakage was reduced by 21% for the uninsulated floor (outside the margin of error) and by 16% for the woodfibre insulated floor (within the margins of error). While there was an improvement in dwelling air leakage with sealed airbricks, it should be noted that air ingress into the floor void is likely not limited to the airbricks, but might also occur through other leakage paths such as services penetrating foundation walls (DeWitt, 1994), however the extent of this was not investigated in this study.

The Saint Gobain study reported that whole house air permeability of 12.5 m^3/m^2hr at 50Pa was reduced to 10.4 m^3/m^2hr at 50Pa after wall and loft insulation and glazing replacement (Fitton, 2014). This was further improved to 6m^3/m^2hr at 50Pa, i.e. a 42% reduction after the addition of 200 mm mineral fibre floor insulation and airtightness measures. To achieve this, Saint-Gobain (2014a, 2014b) replaced all square-edged floorboards with tongue and groove boards and perimeter floor/wall junctions were made airtight in addition to use of an airtight membrane above the joists and the 200 mm mineral fibre insulation, which was held by closed trays in between the joists. However for the Saint-Gobain study it is difficult to separate the impact of other retrofit intervention measures and their impact on overall dwelling airtightness, such as wall insulation impacting floor and wall junctions and whether the base-line airtightness tests were based on the original structure (e.g. part tongue and grooved, part square-edged floorboards) as described in Chapter 4.3. Bell (2000) also reported significant improvement in airtightness after sealing gaps and cracks around windows and doors and the suspended ground floor, though noted that the latter could have been further improved by sealing gaps along the floor edges. Banfill (2011) also reported a 42% dwelling airtightness improvement after installing a membrane over the timber floor and up behind the skirting boards alongside making the floor surface airtight and sealing all service and floorboard gaps and cracks and floor/wall (skirting board) junctions, though acknowledged this was disruptive. These are significant improvements from floor sealing strategies compared to the RdSAP suggested limited improvement (10%) from 'sealing' the floor. The discrepancy between the other research findings and the observed field study findings here, which indicate no significant dwelling airtightness improvements from insulating the floor or from addition of the breather membrane in the woodfibre insulated floor, might possibly be attributed to the exclusion of specific airtightness improvements alongside insulation installation in the field study, unlike in the other studies. Contrary to this, in the field study:

- for woodfibre insulation, a breather membrane was used up and over the joists with overlapping edges taped with airtightness tape, however along the room perimeter, no taping of the membrane was possible due to the skirting boards remaining in place. No membrane was used in the bead-filled floor.
- no floorboard gaps and skirting wall/floor junction cracks were filled,
- the original floorboards were retained,
- the location of the airbricks in between the joists limited any attempt to achieve airtightness along the external perimeter.

It is unknown whether different insulation materials and other interventions might have lead to improved airtightness or not; though as Stevens (2013) noted for solid wall insulation, improved airtightness will be highly variable without specifically improving fabric airtightness alongside the insulation measure.

This indicates that without a deliberate airtightness strategy there might be no significant airtightness benefits from insulating suspended timber ground floors, as also generally reported elsewhere for other construction elements in other retrofit projects, e.g. Banfill (2011); the filling of gaps and cracks is also recommended by several guidance documents to reduce draughts and in order to improve airtightness (for example EST (2007), Rickaby (2014) and BRE (2000)).

6.6. Implications for policy and retrofit decision-making

Using current modelled values, the relatively small floor thermal transmittance might explain why so far the main focus of heat loss reduction has been that of the building's superstructure (i.e. roofs and walls) and not from floors. As such, in some dwelling retrofits the suspended ground floor remained uninsulated, off-setting its predicted heat-transfer with increased insulation elsewhere (TSB, 2012). Clearly, by doing so, ground floor heat-transfer increases proportionally as the rest of the building's fabric is upgraded; it was illustrated that the proportional floor heat-transfer generally became the largest heat-transfer contributor of the opaque fabric elements (disregarding infiltration losses). However, when taking into account in-situ measured floor U-values as found in the field study, proportional floor heat-transfer was significantly higher and hence the impact of insulating the floor might be underestimated.

Furthermore, RdSAP assumes 150mm insulation in between joists, however for the field study just 100mm between joists was practically achievable (unless bead-filled). The modelled performance of 100mm woodfibre insulation between joists met the Part L1B recommended U-value requirements for upgrading floors when using current models, but fell short of these design recommendations when in-situ measured. This was partially explained by installation quality, however such problems are also likely to occur in other buildings.

If the above observations are more broadly confirmed in pre-1919 housing stock, it would have significant implications for policy and retrofit decision-making. For example given the disruption involved in insulating ground floors, they might be left uninsulated if U-values are underestimated by models and if proportional U-value reductions of interventions are also underestimated. The estimated pay-back of upgrade measures on which decisions are based might also exceed the ≤15 year stipulation for regulations to apply, meaning that there would be reduced incentives to insulate floors, when in fact the actual space-heating energy reductions might be much greater than assumed with faster payback. Calculated payback times will differ depending on the extent of exposed perimeter and whether the installation is DIY or carried out by professionals; payback figures were quoted as little as 2 years (WHICH?, 2015) and 3 to 8 years by Thorpe (2015) while 4 to 46 years if the building is gas-centrally heated and depending on insulation method (based on £25/m^2 and £70/m^2 (EH, 2013)).

Payback assumptions are however unclear; and it appears that the 2 years is based on DIY installation (WHICH?, 2015); which can be as little as £100 to as much as £750 for a professional installation; while Shorrock (2005) states £50 to £1000. Dowson (2012) calculated a payback of about 30 years at a cost of £1000 for suspended timber ground floor insulation. Clearly if the payback is based on wrongful assumptions about the floor's initial U-value, the actual payback potential would differ and might reduce the above payback figures significantly, making floor-insulation more cost-effective and with faster payback.

Furthermore, if stock-models assume Part L1B standards for the upgrade of floors (or assume -like RdSAP- 150mm between joists), this might underestimate the actual heat-transfer when the insulated floors do not meet either standards, leading to uncertainty in energy and carbon emission models and associated policy-making. The 15% assumed 'in-use' factor (DECC, 2012) might be underestimated depending on floor characteristics and insulation installation technique and quality. Adjusting modelled values with the 15% 'in-use' factor might align modelled and in-situ measured more closely, however Part L1B recommended design U-values may no longer be met. Despite this, U-values higher than those recommended in Part L1B might help prevent void conditions becoming ideal for mould growth - as argued by Airaksinen (2003), while providing some thermal comfort benefits from insulating floors. Hence undertaking floor upgrades to reduce heat-transfer and compensatory energy use and increase occupant thermal comfort might need to be carefully balanced with the effect this might have on floor void conditions to protect occupant health, though at present these considerations are poorly characterised and further research is required.

The field study findings also indicated that there might be significant benefit in lower disruption heat loss reduction interventions, such as winter airbrick sealing. However, further research is required with regards to the longer term impact of airbrick sealing on the timber floor structure, which was not undertaken in this study. Thermal comfort benefits from sealing the airbricks were inconclusive and more research is required, especially related to occupant perception and impact on room airflow, neither of which were part of the field study. Depending on sleeper wall locations and construction, installing insulation along the perimeter only might also be effective, though further research is required into its efficacy. Given the large proportion of heat-transfer from the ground in especially ground floor apartments, it might be beneficial for retrofit campaigns and policy to prioritise insulation measures for these dwelling typologies.

The significant floor U-value reductions achieved in this field study suggest that scaling-up insulation interventions to the entire housing stock could have a significant impact on energy reduction. Improving the in-situ characterisation of floor U-values and their likely variation will facilitate a more accurate prediction of the current performance and hence supports a more accurate prediction of the impact of interventions in support of carbon reduction policies in the UK housing stock.

6.7. Discussion and summary

Two floor insulation interventions were undertaken in an unoccupied field study house: 100mm woodfibre insulation between joists and bead-filling the void (sealed airbricks). High resolution in-situ heat-flow measurements were undertaken in the same 27 locations on the floor as in the uninsulated floor study. Airbricks were also sealed for the woodfibre intervention to investigate the effect of airbrick ventilation on observed heat-flow. This chapter mainly addressed research question 3 *(How does the in-situ thermal performance of a case study floor change after intervention measures?* "), and supplemented knowledge of floor interventions and also floor airtightness and theoretical thermal comfort comparisons by exploring secondary research question 3.1. ("*What are the thermal comfort implications of insulated and uninsulated floors?)*. For research ethics and generalisability of case-study findings, see Section 3.4.3. and 3.4.4.

As in the previous chapters, several hypotheses were tested and most were supported by the field study analysis and findings; in particular the first part of hypothesis H5:"*There will be a significant decrease observed in thermal transmittance after insulation installation*" was supported with significant reductions in U-values for the woodfibre insulated floor (65%) and 92% for the bead insulated floor. These reductions exceeded the margins of measurement uncertainty and differences in pre/post intervention U_p-values were considered statistically significant. However, dwelling airtightness was not significantly improved post-insulation and H5a was not supported; this might be explained by the lack of specific airtightness measures as part of the insulation intervention.

Additionally, perimeter U_p-values were (statistically) significantly larger compared to the non-perimeter zone (H2), though significantly reduced for the bead-insulated floor (H2a), which also had a reduced spread of point U-values (H4). The reduced spread for insulated floors (H4) was only observed for the bead-insulated floor and was not observed in the woodfibre insulated floor, possibly due to insulation installation inhomogeneities. The effect of sealing of airbricks on heat-flow reduction could not be ascertained for the woodfibre insulated floor due to data quality issues, hence hypothesis H3 and H3a could not be tested.

In addition, for the field study it was found that the discrepancy between modelled and in-situ estimated U-values reduced the better insulated the floor was. While the modelled versus in-situ measured U-value gap was reduced for insulated floors, current models appeared to underestimate the proportional efficacy of insulation interventions; they significantly underestimated the initial U-value of the uninsulated floor - see Chapter 5. The superseded CIBSE-1986 model outputs also appeared to more closely align with in-situ measured values, however further research is required in a larger sample whether this is accidental or due to being a better floor U-value model-fit. Adjusting the woodfibre insulated floor model to take account of installation quality issues after in-situ observations, slightly reduced the divergence between modelled and in-situ U-values. This highlighted also the value of in-situ measurements for model accuracy. Despite this, the woodfibre insulated floor U-value - as in-situ estimated - fell short of the design values recommended by Part L1B building regulations. Using a different material with lower thermal conductivity should lead to a better in-situ thermal performance; however lower conductivity insulation might be limited to those (vapour-impermeable) materials not recommended by English Heritage (EH, 2010) - see *Appendix 2.B.* Furthermore, better performing insulations often tend to be rigid boards which are more difficult to cut and install between uneven joist spacings. A solution might be to insulate the perimeter with lower conductivity materials to reduce the limitations of these materials and to maximise the heat-flow reduction impact in the areas of greatest heat-transfer. Depending on sleeper wall location and connecting openings to the rest of the void, perimeter insulation only might also be effective; further research would be required into the efficacy and practicality of doing so.

The field study also reiterated the value of high-resolution monitoring and the limited value of low-resolution measurements to derive the whole floor U-value; uncertainty associated with this slightly decreased when floor insulation significantly reduced the spread of U_p-values across the floor, i.e. for the bead insulated floor in this study with sealed airbricks. Nevertheless the reduced spread of U_p-values might not occur post-insulation because airbricks are normally kept open; thus a substantial spread of U_p-values might remain. Hence low resolution in-situ pre/post studies are also likely at risk of over-or underestimating the insulated floor U-value and the insulation efficacy, depending on the observed locations.

Other issues highlighted from this study were that good installation quality might maximise heat-flow reduction, such as a tight fit between insulation material and joists and floorboards and special attention along the perimeter walls and near airbricks is likely required. Upgrading of floors might lead to increased occupant thermal comfort, however generally the floor surface temperatures did not meet thermal comfort thresholds pre-or post insulation, though some limited evidence supported H6 that thermal comfort was improved post-insulation. This was mostly evidenced with (statistically significant) warmer floor surface temperatures (though generally still below theoretical thermal comfort thresholds). There was also a shorter duration of head-toe temperature differences >3ºC when seated or standing; though these latter improvements were small in this field study. As noted above and contrary to other research, no increased airtightness was observed post-insulation, likely due to the lack of specific airtightness measures undertaken alongside the interventions and partly because of difficulty in insulation installation along the perimeter and near the airbricks. This indicated that without specific airtightness measures while installing floor insulation, there might be a missed opportunity for improved airtightness. However, as noted by Stephen (1998) and Henschel (1992), making the floor more airtight is likely to change floor void ventilation and this might effect mould growth risk, though this is poorly characterised and has been noted for further research. Upgrading floors also changes floor void conditions, which in some countries lead to moisture build-up and mould growth in floor voids (see Chapter 2). These organisms can then affect building structure and occupant health if mould spores transfer into living spaces above. Due to short-term measurements, this study could not evaluate floor voids pre/post insulation interventions; short-term monitoring periods are not a good indicator of floor void conditions: the variables are influenced by the seasons and hence longer term monitoring is required to take account of the fluctuating seasonal conditions that occur in voids - see discussion in Chapter 2 and Chapter 5.3.7.3.

The field study also lead to practical insights, useful for future in-situ measuring and intervention studies. Those listed below are in addition to those already reported above or in Chapter 4.5 and 5.5.:

- The high resolution in-situ heat-flux measurements approach was able to quantify the efficacy of pre/post interventions outside the margins of measurement uncertainty. Further research is required to investigate if this remains the case for more subtle interventions, such as addition of radiant barriers, carpet etc.

- Generally for the field study it took between 9 and 15 days to obtain valid U-value results with unsealed airbricks, however in-situ heat-flux measurements later in March were found to be problematic due to changing environmental conditions.

- Long-term floor void monitoring is required to ensure seasonal changes are captured.

Several areas for further research were highlighted, including pre/post insulation studies in a larger and diverse sample; long-term monitoring of void conditions and floor system heat-flow at high-resolution. Other further research areas include occupant responses to draughts and cold feet, research into compensatory energy use due to local thermal discomfort, floor airtightness (including void pressurisation/tracer gases); characterisation of UK floor voids, impact of floor insulation on the whole house (changes to void airflow etc.). Measuring a large sample of a variety of different floors are required to test the above observations in the pre-1919 housing stock and to confirm any implications for policy and retrofit decision-making.

Chapter 7: Conclusions, reflections and further research

7.1. Introduction

Understanding the actual versus the predicted performance of a construction element is important to ensure that appropriate retrofit decision-making and intervention choices support carbon reduction policies and meet carbon reduction targets. There are millions of UK properties with suspended timber ground floors, yet at present the actual thermal performance of such floors and the impact and the implications of insulating them are poorly characterised. The primary purpose of this PhD research was to investigate the thermal performance of suspended timber ground floors and how to estimate in-situ floor U-values. The research aimed to gain and add to the understanding of the actual performance of uninsulated floors and the heat loss reduction potential of interventions and what the benefits and drawbacks of insulating such floors might be. The following research questions were raised:

1. **How should in-situ suspended timber ground floor U-values be estimated?**
2. **What is the in-situ measured thermal transmittance of floors and how does it compare to model predictions?**
3. **How does the in-situ thermal performance of a case study floor change after intervention measures?**

    3.1 *What are the thermal comfort implications of insulated and uninsulated floors?*

In response to these questions, six hypotheses were developed as listed in *Table 42*. These hypotheses were tested by undertaking in-situ heat-flux measurements in the Salford Energy House (STUDY 2) and in a field case-study house (STUDY 4A). The impact of sealing of airbricks on estimated thermal transmittances was investigated in both studies, while STUDY 4A was also subject to two insulation interventions: full-fill EPS-bead insulation in the floor void and woodfibre insulation between the joists (STUDY 4B). This concluding chapter draws together the different research findings, policy implications and opportunities for further research, alongside overarching reflections on these results. For ease of reference and where relevant, the hypotheses numbers (see *Table 42.*) have been added in brackets.

H1. There will be a large observed spread of U_p-values across the uninsulated floor	See Chapter 4 and 5
H2. There will be increased perimeter U_p-values observed compared to locations further away from the external wall (i.e. the non-perimeter zone). **H2a. This will be observed both for insulated and uninsulated floors, albeit reduced for the latter.**	See Chapter 4 and 5 See Chapter 6
H3. There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks. **H3a. and this effect will be proportionally smaller in insulated than in un-insulated floors.**	See Chapter 4 and 5 See Chapter 6
H4. There will be a reduced spread of U_p-values observed for the insulated floor compared to the uninsulated floor.	See Chapter 6
H5. There will be a significant decrease observed in thermal transmittance after insulation installation. **H5a. insulation will also be observed to improve dwelling air tightness**	See Chapter 6
H6. Post-insulation it will be observed that thermal comfort is improved.	See Chapter 6

Table 42. Research hypotheses

7.2. Summary findings

The main research findings, based on primary data collected in two main studies and two exploratory studies are summarised below. For summary of undertaken studies, see *Table 43.* below.

- Overall there was a large spread of U_p-values across the uninsulated floor (H1), with increased thermal transmittance along the perimeter compared to the non-perimeter floor zone (H3). This was observed in both STUDY 2 and 4A.
- Sealing of airbricks reduced the whole floor thermal transmittance of the uninsulated floors(H4) by 17% and 31%, as observed in STUDY 2 and STUDY 4A[1] respectively.
- The large variation of U_p-values across the floor and the perimeter effect reduced once the floor was insulated (H2a, H3a), however these effects appeared dependent on installation method and quality (STUDY 4B).
- STUDY 4B also verified the significant U-value reductions achieved after insulation interventions (H5), achieving average whole-floor U-value reductions of 65% and 92% for the woodfibre insulated and EPS-bead insulated floor respectively.
- However, improved dwelling airtightness after insulating floors (H5a) was not observed in STUDY 4B, which suggested that separate attention to airtightness measures are likely to be required to improve airtightness in this study.
- While some key thermal comfort indicators appeared slightly improved for insulated floors (H6) (especially warmer floor surface temperatures), the floor studied did not meet several thermal comfort thresholds, even post-insulation.
- A divergence between modelled and in-situ measured U-values was observed, for both STUDY 2 and STUDY 4A, where current models seemed to underestimate in-situ estimated U-values. However further research is required to investigate if this disparity exists across the wide housing stock and what the causes of this disparity are.
- In STUDY 4B it was observed that this modelled and in-situ measured disparity reduced the better insulated the floor was.

A particularly important conclusion that can be drawn from the in-situ data is that, because of the perimeter effect and the large variation of U_p-values across the floor, a limited number of point measurements are highly unlikely to be representative of the whole floor's U-value and hence would not provide data suitable to be compared with theoretical models, which are based on whole floor U-values.

[1] For Study 4 there was considerable uncertainty due to the short-term monitoring period. See Chapter 5.3.7.

As such high-resolution measurements, planned to capture as much of the floor heat-flow heterogeneity as possible, are required to obtain an accurate estimate of the whole floor U-value. Additionally in-situ measurements indicated that current theoretical models appeared to significantly underestimate whole floor U-values. However this discrepancy might not be as large as other studies initially suggested because these studies are based on a few point measurements, which provide a poor estimate of the whole floor U-value. The superseded CIBSE-1986 model seemed closer aligned with the in-situ measured U-values, however further high-resolution case-studies are required to investigate if the CIBSE-1986 model is a better predictor of actual suspended floor U-values or whether the disparity between modelled and measured values due to conceptual differences between both. Likewise further research is required to investigate whether the above findings are confirmed in the wider pre-1919 housing stock.

Furthermore, in-situ measurements highlighted the effects of data collection and analysis procedures in introducing uncertainty around the estimated point and whole floor U-values, as illustrated by the differences resulting from the use of surface or air temperatures for the determination of U-values - see Chapter 4 and 5. The use of surface temperatures - as was done throughout this research - requires the addition of a surface thermal resistance (R_{Si}= 0.17 m^2KW^{-1}), which has a proportionally greater effect for floors with low thermal resistance (i.e. uninsulated floors, see Chapter 6). At present the U-value adjustment by this constant value is not well characterised for suspended timber ground floors in practice.

More detail and a brief discussion about each of the above main findings is presented in the following sections.

<table>
<tr><th>STUDY 1
Field study
London</th><th colspan="2">STUDY 2
Salford EH</th><th colspan="2">STUDY 3
Pre-post pilot Manchester</th><th colspan="5">STUDY 4 (A & B)
Field study Ealing</th></tr>
<tr><td>Pilot study (2012)</td><td colspan="2">Initial study (2013)</td><td colspan="2">Pilot study: pre-post insulation intervention study (2013)</td><td colspan="5">Field study: pre-post insulation intervention study (2013-2014)</td></tr>
<tr><td rowspan="2">Field study, London occupied house; low-resolution monitoring: 2 locations on floor</td><td colspan="2" rowspan="2">Salford Energy House, environmental chamber; high resolution monitoring: 15 locations on floor</td><td colspan="2" rowspan="2">Manchester region, unoccupied house ; low-resolution monitoring: 4 locations on floor</td><td colspan="5">West London, unoccupied house; high resolution monitoring: 27 locations on floor. Additional monitoring of environmental variables, as well as monitoring of airtightness, floor void and thermal comfort variables pre-post interventions.</td></tr>
<tr><td colspan="2">STUDY 4 A
Field study Ealing
(pre-insulation)</td><td colspan="3">STUDY 4 B
Field study Ealing (post-insulation)</td></tr>
<tr><td>Uninsulated</td><td colspan="2">Uninsulated</td><td>Uninsulated (pre)</td><td>Insulated (post)</td><td colspan="2">Uninsulated floor (pre)</td><td>EPS bead insulated floor (post)</td><td colspan="2">Woodfibre insulated floor (post)</td></tr>
<tr><td>Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td colspan="2">Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td>Sealed airbricks</td><td>Open airbricks</td><td>Sealed airbricks</td></tr>
<tr><td>March 2012- April 2012</td><td colspan="2">May 2013</td><td>September 2013</td><td>October 2013</td><td colspan="2">January 2014</td><td>End of January 2014-mid-February 2014</td><td>February-March 2014</td><td>mid-March 2014</td></tr>
<tr><td>Chapter 4</td><td colspan="2">Chapter 4</td><td colspan="2">Chapter 3 & 6/Appendix</td><td colspan="2">Chapter 5</td><td colspan="3">Chapter 6</td></tr>
</table>

Table 43. Summary table of the different studies undertaken.

7.2.1. Floor U-values

This section summarises the findings related to the first part of the second research question "*What is the in-situ measured thermal transmittance of floors and how does it compare to model predictions?*".

The analysis of the data presented in Chapters 4 and 5 demonstrated that - in line with physical theory - suspended timber ground floors had increased thermal transmittance along the perimeter (H2). There was also a large variation of U_p-values (H1), related to the varying airflow through airbricks and distance from the exposed perimeter walls. It was also observed that increased sub-floor ventilation through open airbricks increased the thermal transmittance compared to sealed airbricks (H3). These effects were clearly observed in the Salford EH (STUDY 2) and the field case-study (STUDY 4A), though for STUDY 4 there was considerable uncertainty due to the short-term monitoring period - see Chapter 5.2.3 and 5.3.7.

The specific results observed in these two cases are not directly representative of the entire pre-1919 housing stock, however the trends arising from physical principles are likely to be transferable. The analysis of these two studies also highlighted that some dwelling-specific characteristics can interact with the theoretical expectations. For instance, in both cases the floors had structural properties affecting the airbrick airflow in the void: sleeper wall presence in STUDY 4 and joist direction and large joist depths in STUDY 2 might have enhanced the perimeter effect by acting as an obstruction to airflow to the rest of the void and buffering other floor areas, leading to lower observed U_p-values elsewhere. This highlights that the research needs to be considered on a case-by-case basis if detailed knowledge is required.

Furthermore, in the field study low void airflow was measured away from the airbricks, though the results from one single dwelling can only highlight that this observation needs to be verified in a larger sample to identify whether this is a general phenomenon or specific to this dwelling and/or due to how the research was undertaken and how the data was collected, as discussed in Chapter 5. Two further important parameters that need to be analysed in a larger sample are the number and position of airbricks (below or between joists) as a function of floor area and exposed perimeter to understand the impact of these variables on floor thermal transmittance better.

In summary, the results presented in Chapters 4, 5 and 6 have shown that the variation of U_p-values across the floor and the perimeter effect (and 'airbrick effect') are a general floor thermal performance trend and at the same time are an intrinsic property of each floor and dependent on each floor's characteristics.

7.2.2. In-situ heat-flux measuring techniques

This section addresses the first research question *"How should in-situ suspended timber ground floor U-values be estimated?"*. The research highlighted that recording representative and repeatable in-situ measurements as well as transparency about analysis and uncertainty estimation are an essential component of insightful research and performance evaluation to enable comparison between studies and with models. Chapters 3, 4, 5 and 6 highlighted the complexity of estimating in-situ U-values for suspended timber ground floors and comparing these results with models and other studies. Particularly significant are the impact of different data collection and analysis techniques, especially sensor positions, monitoring research design and analysis techniques on estimated U-values. The inhomogeneity of room temperatures makes the use of air temperatures for the determination of floor U-values challenging: depending where air temperatures were measured, different U-values were estimated. While use of surface temperatures is more practical and might be more replicable, this also had associated uncertainties due to the addition of a constant surface thermal resistance; though in the field these results were observed within the margins of error. Further research is required in this area.

It was observed that low-resolution in-situ pre-post studies are at risk of over- or underestimating the insulation efficacy, depending on where measurements were made. Hence a high-resolution in-situ measuring approach, i.e. where many point-locations on the floor are monitored, is generally applicable, and reduces the biases that perimeter effect and construction heterogeneities are likely to cause to low-resolution measuring approaches. Comparing U-values obtained from paired sensors with the whole floor estimated U-value highlighted the limitations of low-resolution monitoring. Based on STUDY 2 and STUDY 4, only a small proportion of the paired sensor locations would overlap with the whole floor U-value error margins obtained from high-resolution monitoring. For this small proportion, generally combinations of two central floor locations or a combination of one perimeter and one rear point location were closest to whole floor U-values, though sensors in central floor locations might not be practical to monitor in occupied dwellings. The better insulated a floor, the lower the spread of U_p-values as was the case for the bead-insulated floor (with sealed airbricks).

In these conditions a low-resolution measurement might have a slightly better chance of reflecting the whole floor U-value; however it is often not until measuring at high resolution that the above can be confirmed. A large uncertainty still remains when obtaining whole floor U-value estimates from just a few point measurements. Additionally, further high-resolution monitoring in a larger sample is required to investigate if these observations are more broadly confirmed. A high-resolution measuring approach is especially valuable when comparing whole floor in-situ U-values to models, because models treat the floor as a whole, and thus the in-situ measurements must be strongly representative of the whole floor. High resolution monitoring is also required to understand the effect of a different number of airbricks, sleeper walls etc.

Finally, in-situ measurements have a level of uncertainty associated with the estimation of U-values, such as instrument error (intrinsic), measuring condition errors (extrinsic errors) and the natural variability of U over the monitoring period as an inherent characteristic of an element's actual thermal transmittance in dynamic situations. The applied uncertainty estimation in this thesis drew on the ISO-9869 standard for intrinsic and extrinsic error estimates. However the natural variability of U was estimated by the standard deviation (*sd*) of daily or hourly U-values in the field or in the thermal chamber respectively. U-values and their final uncertainties must be clearly communicated to instil confidence in findings and comparisons between studies and interventions so as to avoid drawing inaccurate conclusions.

The refined in-situ heat-flux measuring techniques developed in this research (including error- and data analysis techniques and presentation of results) and the value of high-resolution data collection have wider applicability and transferability and are likely to be advantageous to in-situ heat-flux monitoring campaigns of other construction elements.

7.2.3. Predicted versus measured U-values

This section addresses the second research question *"What is the in-situ measured thermal transmittance of floors and how does it compare to model predictions?"*

U-value models are based on simplified inputs and assumptions and the floor is modelled as a whole. Both models and in-situ heat-flux measurements are two complementary approaches to the understanding and determination of whole floor U-values. Models take advantage of physical theory, which require in-situ measurements to be validated and refined.

In-situ heat-flux measurements take advantage of the theoretical framework of models to identify and refine what and where to measure in a real world setting. Differences between models and in-situ results provide an opportunity to understand more deeply both approaches and improve both. However, at present in-situ data is generally based on few floors measured at low resolution, which hinders both the advancement of both in-situ measuring techniques for floors and validating modelling approaches. The data presented in this thesis is thus an opportunity to start to evaluate how and why high-resolution in-situ data and models differ.

While whole floor in-situ U-values estimated from high-resolution monitoring allowed direct comparison to models, other model assumptions made the direct comparison of results less straightforward (e.g. assumed negligible ground thermal mass, assumed material conductivities, wind-speeds etc.). Additionally, there might be some conceptual differences between modelled and in-situ measured floor U-values: for instance inhomogenous room temperatures, short-term thermal mass effects and dynamic external conditions occur in reality while floor U-value models assume annual steady-state heat-flow as a proxy for seasonal heat-transfer. Floor U-value models also exclude linear floor/wall thermal bridge junctions; but in-situ measurements might have been affected by heat-flow through such junctions. It remains unclear however what the individual or combined impact is of these variables on the modelled outputs and how this affects comparison with in-situ measurements - further research is required.

For both high-resolution STUDY 2 and STUDY 4A, U-values from current models appeared to underestimate the in-situ measured whole floor U-values (e.g. 1.04±0.12 Wm^2K^{-1} for STUDY 4A versus 0.57 Wm^2K^{-1} when modelled with ISO-13370). In STUDY 4B, the divergence between modelled and in-situ measured floor U-values reduced the better insulated the floor became: 0.36±0.11 Wm^2K^{-1} in-situ measured versus 0.23 Wm^2K^{-1} modelled and 0.09±0.03 Wm^2K^{-1} in-situ measured versus 0.08 Wm^2K^{-1} when modelled, for woodfibre and bead insulated respectively. Different input assumptions and different models could significantly diverge U-value predictions, such as assumed ground conductivities and assumed airbrick openings and wind-speeds. For the floors studied, the withdrawn CIBSE-1986 floor U-value model appeared to better match the in-situ measured whole floor U-value compared to the other (more recent) models, though this match was also very dependent on model assumptions and further research is required to investigate if this model is a better predictor of actual floor U-values.

The importance of model assumptions and the value of actual in-situ survey information could be seen when adjusting the woodfibre floor U-value model following in-situ observations of reduced perimeter insulation near airbricks and presence of airgaps. Adjusting modelled U-values for this slightly reduced the divergence between modelled and in-situ U-values, highlighting also the value of in-situ measurements for increased model accuracy. However, further research is also required whether the disparity between modelled and measured values is real or due to conceptual differences between both.

Based on STUDY 4B, current models slightly underestimated the efficacy of insulation interventions, mainly because they significantly underestimated the initial uninsulated floor U-value. If these findings are more broadly confirmed for a larger sample, it could have potentially large impacts on homeowner choices and policy direction for the UK housing stock.

7.2.4. Insulating floors: impact on floor heat loss and thermal comfort

The third thesis research question "*How does the in-situ thermal performance of a case-study floor change after intervention measures?*" and its related question (3.1.) *"What are the thermal comfort implications of insulated and uninsulated floors?"* are important given that there are millions of floors yet to be insulated but it is unknown what the actual benefits of doing so are.

Chapter 6 demonstrated that insulating floors can lead to significant U-value reductions (overall 65% reduction with 100mm woodfibre, and 92% when full-filling the void with EPS beads and sealing airbricks). Both the modelled U-values of the floor interventions met the recommended regulatory recommendations for floor upgrades. However, despite the significant thermal transmittance reductions, the in-situ estimated woodfibre insulated whole floor U-value fell short of the recommended regulatory design value. This was because the in-situ estimated floor U-value was initially higher than assumed, while models also excluded installation quality issues and areas of reduced insulation. However the discrepancy between modelled versus in-situ measured values reduced the better insulated the floor. The bead filled void intervention met the recommended regulatory U-values for upgrading floor structures, however there may be unintended consequences associated with this intervention, which were not investigated here due to the short-term monitoring intervals.

After insulation the perimeter effect was reduced, though a reduced spread of U_p-values was only observed for the bead insulated floor, due to the sealing of the airbricks and introduction of a large thermal resistance in the void. However, the woodfibre insulated floor still had a large spread of U_p-values, likely due to the open airbricks and insulation installation heterogeneities. This result highlighted that installation quality is likely to be important to maximise thermal transmittance reduction: a tight fit between insulation material and joists and floorboards is essential to avoid thermal bypasses; special attention along the perimeter walls and near airbricks is required - though this may be easier to achieve in dwellings with airbricks below instead of in between joists. No increased dwelling airtightness was observed post-insulation for the woodfibre floor studied due to the lack of specific airtightness measures undertaken alongside the interventions and due to insulation installation quality near the perimeter and airbricks. Sealing of airbricks however improved dwelling airtightness, and was measured outside the margins of error for the uninsulated floor but within the margins of error for the insulated floors. For STUDY 4B, the findings indicate that without taking specific airtightness measures while installing floor insulation, there might be a missed opportunity for improved airtightness.

Energy and carbon reductions are not the only reasons to consider upgrading floors: a benefit of insulating the ground floor is to increase occupant thermal comfort. Given that the studies were undertaken in unoccupied spaces, no occupant thermal comfort surveys were undertaken but instead comparisons of monitored variables were made against thermal comfort thresholds. The results presented in Chapter 6.5. indicated that thermal comfort might be positively affected by insulating the floor (especially warmer floor surface temperatures), though generally the improvements were small and even after insulation, the thermal comfort thresholds were not met.

Due to the short-term nature of the insulation interventions, the impact of insulation on floor void conditions could not be studied and this has been highlighted for further research.

7.3. Research limitations and further research

The case-study approach used in this thesis could not provide population-wide inferences, though it allowed testing specific hypotheses, which can be the basis for further work and wider generalisation. A number of limitations (some, such as case availability, were unavoidable) became apparent both in the research approach and in the data available, though understanding these limitations presents novel and further research opportunities. Throughout this research it became apparent that both longer-term studies and larger samples are necessary to investigate whether the trends and observations from this research replicate across other floors and to be able to infer strong conclusions for the wider UK housing stock. Five main and interconnecting areas for further research were identified and are discussed overleaf.

A. High-resolution floor heat-flow should be monitored in a much larger sample, including different dwelling types and floor and void typologies and located in different UK geographical locations to understand if the research findings transfer to the wider UK housing stock. Secondly, longer measuring periods to improve the understanding of seasonal influences, and measurement of model input variables might help to refine model input assumptions and reduce disparities between modelled and in-situ measured U-values (and help clarify the impact of some of the conceptual differences). In particular it might be useful to measure party-wall and foundation wall heat-fluxes, ground temperatures, moisture content and ground heat-fluxes at different depths. Such additional variables might also aid model refinement and investigation of other models, including the development of archetype (floor) stock models and studies of linear thermal bridging. Further investigation of void obstructions (e.g. sleeper walls) and impact on sub-floor heat-flow and airflow (requiring multi-directional void measurements) would add to this study. Further research might include additional air temperature measurements and room airflow to investigate the thermal resistance of the surface boundary layer across the floor. Isolating the effect of void service pipes and the 'heat recovery' of downward heat-flow by stack effect would add to the understanding of the complexity of floor heat loss.

B. In-situ measuring techniques could be further refined and developed for occupied houses and for purposeful low resolution measuring to understand the 'minimum' high resolution monitoring needed. Further research into which internal temperatures to use alongside a detailed study of the impact of airflow on surface resistances in different locations on the floor will help refine the data- and error analysis (and model assumptions). Dynamic data analysis might also be beneficial but is undeveloped at present for floors.

Adapting blower-door tests to measure the airtightness of the floor separately and use of void tracer gases would enable a more detailed study of upward floor void airflow in order to understand the floor air leakage paths. Developing larger heat-flux plate transducers - as described by Cox-Smith (2008a) and Isaacs (1985b) - instead of the current heat-flux sensors used might also be of benefit.

C. Thermal comfort implications of cold surfaces, vertical stratification and pre/post insulation interventions need to be further investigated in a larger sample and in occupied dwellings where it is possible to enable occupant thermal comfort surveys. Additionally, further research into compensating energy use from local thermal discomfort (including cold surfaces and upward draughts) is needed to fully understand the implications of occupant discomfort on energy use behaviour. The author received a World University Network (WUN) grant with contributions from the Sheffield School of Architecture and the architecture department at Sydney University to research the "*Effect of uninsulated floors on occupant thermal comfort*" at Professor de Dear's Internal Environmental (IEQ) Lab in Sydney (August-September 2016).

D. Future floor insulation studies would benefit from a wider variety of insulation materials and methods and longer-term in-situ heat-flux measuring both pre-and post-intervention, leading to a financial pay-back analysis of different measures. This should include the investigation into the efficacy of underlay and carpet and perimeter insulation only, and the viability of sealing of airbricks over winter alongside RH monitoring as less disruptive and more cost-effective heat loss reduction solutions. More research is also required to fully understand the impact of insulation installation and airtightness practices on the efficacy of floor heat loss interventions, which can inform industry practice. Finally, research is required to investigate changing floor void conditions and the impact of insulating the floor on neighbouring (uninsulated) floors and vice versa.

E. mould growth risk research was significantly constrained in this study due to the short-term nature of the study. Mould growth is a precursor to fungal decay and structural damage, and an important consideration is that mould spores could transfer from the void to the living space, and can pose a health hazard. Undertaking floor upgrades to reduce energy use and increase occupant thermal comfort need to be carefully balanced with the effect this might have on floor void conditions, however the possible risks of insulation in terms of mould or fungal growth are poorly characterised in the UK. Hence it will be important to focus on long term pre/post intervention monitoring to investigate the effects of airbrick sealing and how void conditions change after insulation for a variety of case-studies.

A long-term monitoring programme of a large sample of (for example ECO-insulated floors) would support this investigation, alongside development and validation of mould growth models specifically for pre-1919 UK suspended ground floors. Finally, long term characterisation of void ventilation, stack airflow and pressure differentials between void/external/internal spaces with air sampling might support increased understanding of mould spore transfer to indoor spaces, and support their potential health effects. The impact of different ventilation mechanisms and improved airtightness as part of building retrofit on void air flow also requires further study. This research is intended to be expanded in collaboration with Professor Airaksinen at VTT in Finland.

7.4. Policy implications

Despite slow uptake of floor insulation, thousands of floors were insulated as part of the ECO-policy, yet the impact on heat loss reduction and on thermal comfort and floor void conditions remains poorly characterised. STUDY 4B demonstrated that significant U-value reductions could be achieved by insulating floors. As there are millions of uninsulated floors, scaling-up those reductions could lead to potentially significant energy and associated carbon emissions reductions across the existing housing stock. However, a better understanding of the impact of heat loss reduction measures on floor void conditions is critical to avoid jeopardising occupant health - as highlighted in further research.

STUDY 4 highlighted that proportional floor heat-flow might be significantly greater than assumed at present and that estimated proportional U-value reductions might exceed those assumed by models. If these above observations are more broadly confirmed in the pre-1919 housing stock, it might create a barrier to robust retrofit decision-making for consumers, industry and policy-makers. Firstly, if the floor U-value is underestimated and if efficacy of interventions is also underestimated, floors might be left uninsulated, possibly compounded by the disruption involved in insulating ground floors. Secondly, the estimated pay-back of upgrade measures on which decisions are based, might also exceed the ≤15 year payback stipulation for regulations to apply, reducing incentives to insulate floors. Yet in reality the actual space-heating energy reductions might be much greater than assumed with faster payback. Thirdly, a low floor U-value prediction discourages the insulation of floors, focusing attention on other fabric interventions such as walls and roofs first. This strategy might be particularly flawed for ground floor apartments as proportional floor heat-transfer is likely to be more significant than other fabric elements. Finally, erroneous assumptions about the final floor performance post-insulation can lead to erroneous stock and forecasting models based on those assumptions.

The first step to reducing these possible uncertainties is a high-resolution in-situ measuring campaign of a larger sample and variety of floors, as described in the previous section. Further possible policy implications, which require further study of floors:

- There are uncertainties associated with floor U-value models, including ISO-13370 on which (Rd)SAP is based and which is used in the UK for regulatory approval, policy and funding decision-making. Research is required into the model assumptions and suitability of its conceptual approach for suspended timber ground floors to ensure policy and retrofit decision-making is underpinned by suitable models.
- Default RdSAP assumptions lead to a certain percentage improvement in dwelling airtightness from insulating floors. However, this study supported other research suggesting that without specific additional floor airtightness measures, airtightness improvements might be limited. Likewise, default RdSAP assumptions are 150mm insulation in between joists, which might often not be achieved because of joist depth and airbrick locations. Policy-making must reflect the practical limitations of achieving this level of insulation and airtightness and this should be reflected in stock models and energy-reduction assumptions and allowed for in payback assumptions and models. For instance, the woodfibre insulated in-situ floor U-value in this study fell short of meeting the recommended regulatory and modelled floor U-value post-intervention due to technical detailing and installation quality issues likely to exist in other floor insulation installations elsewhere. At present guidance for floor insulation is limited and little attention is given to practicalities and details of insulating floors. Industry and policy guidance could highlight the importance of separate airtightness measures and insulation installation quality to maximise floor heat loss reduction.
- It is unknown whether the current regulatory design U-value recommendations for floor upgrades have a negative impact on floor void conditions and associated occupant health. Thus regulatory recommendations and tools such as RdSAP should be based on much larger in-situ evidence and recognise practical and technical limitations, as well as inter-connections between floor U-values and floor void humidity and risk of mould growth and associated risks to occupant health issues.
- Due to the decision-making implications, researchers themselves need to be aware of the uncertainties associated with modelling and in-situ estimated U-values and communicate them clearly to policy-makers and industry. Government policy especially should be made with these uncertainties in mind.

Clearly, improving the in-situ characterisation of floor heat loss and their likely variation will facilitate a more accurate prediction of the current performance and hence supports a more accurate prediction of the impact and risks of interventions in support of carbon reduction policies in the UK housing stock.

7.5. Conclusion

In summary, this research contributed to an increased understanding of suspended timber ground floor thermal performance and methodological approaches of in-situ measuring of floors. The practical difficulty of having access to floors and instruments for research purposes meant that only a few cases were available for in-situ measurement. Nevertheless the in-situ results verified physical theory and that there was a large spread of U_p-values across the uninsulated floor with increased U_p-values closer to the exposed perimeter. The large variation of U_p-values across the floor and the perimeter effect remained but reduced for the insulated floor. Furthermore, based on the few case studies, disparities between in-situ measured and modelled floor U-values were identified and suggested that current floor U-values may underestimate the actual floor system's thermal transmittance. This modelled and in-situ measured disparity reduced the better insulated the floor was.

Significant thermal transmittance reductions were achieved from insulating the floor (between 65% and 92%, depending on method), however improved dwelling airtightness after insulating floors was not observed. Improved airtightness of up to 21% was observed for sealing of airbricks, which also reduced the floor U-value (17 to 31% depending on case study)[2]. Some key thermal comfort indicators appeared slightly improved for insulated floors, but the floor studied did not meet several thermal comfort thresholds, even post-insulation. With regards to floor void conditions, longitudinal studies are required for analysis and this was outside the scope if this PhD research.

The data collected for this thesis highlighted that the thermal behaviour of floors is complex and affected by a number of environmental and structural factors. Interventions aiming to change the thermal behaviour of floors are themselves affected by those environmental and structural factors which need to be considered to maximise the benefit of floor insulation. This thesis research also identified a number of issues (measuring approaches, actual U-values, heat loss reductions from interventions, model versus in-situ measurement disparities) with significant practical and policy implications. It also highlighted the importance of appropriate data uncertainty assessment and the need to report research findings and procedures transparently.

[2] For Study 4 there was considerable uncertainty due to the short-term monitoring period. See Chapter 5.3.7.

Furthermore the methodological considerations about in-situ floor measurements are likely to have wider applicability to other cases and research of floor U-value estimations in the future: a direct implication of the large spread of U_p-values is that a limited number of U-value point measurements are highly unlikely to be representative of the whole floor's U-value. Instead, high-resolution measurements are required, which is a departure from current monitoring campaigns. Furthermore, the refined in-situ heat-flux measuring techniques, including high-resolution data collection developed in this research, have wider applicability and are transferable to in-situ heat-flux monitoring campaigns of other construction elements.

Finally, if the modelled underestimation of actual floor U-values is more broadly confirmed in the pre-1919 housing stock, it would have significant implications for policy and retrofit decision-making.

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Appendices

Appendix 2.A: Summary table model assumption inputs

Identified assumptions and excluded inputs in the ISO 13370 model – adapted from (Pelsmakers, 2012)

Model inputs	ISO 13370 (BSI, 2009b) and CIBSE GUIDE A (CIBSE, 2015)	Published range/other sources?	Published in-situ measurements? (excluding associated uncertainties)	Notes/issues
INPUT ASSUMPTIONS				
Water table	No allowance made: ground water in most cases is not at shallow depth and considered to have a negligible effect.	Depending on depth (z_w), needs to be multiplied with ground water factor (G_w) and 1≤G_w≤ 1.16 (BSI, 2009b)	-	Depending on water table depth and water flow, thermal conductivity is different. (Thomas, 1999) argues that moisture content variations near floor boundaries are likely to have an effect on heat loss. (Janssen et al., 2004) found that for a solid concrete floor slab with basement, 'the influence of soil moisture transfer on building heat loss via the ground is [illegible] negligible' and [illegible] its exclusion in ISO 13370.
Thermal properties soil	If conductivity soil (λ_s) is unknown, representative values are to be used: 1.5 W/mK for clay or silt; 2 W/mK for sand/gravel and 3.5 W/mK for homogeneous rock.	Ranges listed in ISO 13370, from 0.2 to 4.5 W/mK depending on soil/moisture content. For clay: 0.9-1.4 W/mK (BSI, 2009b); 0.27- 2.1 W/mK (Davies, 1993) and 0.15-4 W/mK with 0.15 to 1.8 for dry to moist clay (Hukseflux, 2012).	1.5-2.57 W/mK (Adjali et al., 2004)	Soil thermal conductivity is dependent on the kind of soil (which is often unknown) and also moisture content, which is likely to fluctuate throughout the year and from site to site – see above. While the soil under (solid) ground floors is likely to be dry, along the floor edges variations in moisture content and hence heat loss are likely to occur (Rees, 2001; Thomas, 1999). The greater the moisture content, the higher the U-value and (Adjali et al., 2004) noted that simplification of models and input assumptions over or under estimated the actual heat-loss.
	Assumed soil heat capacity per volume ($\rho_s c$) = 2.0 x 10⁶ J/m³K	$\rho_s c$ varies between 2.0 x 10⁶ J/m³K and 2.94 x 10⁶ J/m³K depending on soil type (BSI, 2009a).	2 W/mK (Adjali, 2000)	The model also ignores inhomogeneity in soil which also affects the soil's thermal conductivity and thermal mass and hence floor heat-loss (Khaled et al., 2012).
Internal and external surface resistances (R_{si} & R_{se})	R_{si} = 0.17 m²K/W for downward heat-flow, assumed at 20°C internal temperature (BSI, 2007). R_{se} = 0.04m²K/W, based on external wind speed of 4 to 5m/s (BSI, 2007).	R_{se}: 0.08-0.02 m²K/W, depending on wind-speed from 1m/s to 10m/s respectively (BSI, 2007).	-	R_{si}/R_{se} are based on assumed environmental conditions and are considered a constant, when in effect they are not. ISO 6946 (BSI, 2007) notes that surface resistances are an approximation only and do not take into account for example geometry/obstructions and forced convection. (Harris, 1995) observed that increasing airflow in the sub-floor void, reduces the surface thermal resistances, as discussed in Chapter 2. Use of R_{si} on both sides of the surface in calculation of U instead of R_{se}.
Ventilation opening	Suggested size of 0.0015 or 0.0030 m²/m, but actual ventilation openings can be used if known.	CIBSE (2015) assumes the same as ISO 13370. RdSAP (BRE, 2011) typically assumes 0.0030 m²/m; 0.015 m²/m is the minimum recommended by Building Regulations, Part C (NBS, 2013).	No large scale surveys to verify these statistics. These assumptions are for the pre-1919 stock; the 2012 pilot study and Salford EH had less than this - see Chapter 4.	Assumptions about geometry of air-bricks: assumed to be open and not blocked by objects and/or dust/spider webs. As adjusted by (Williamson, 2006) who proposes a reduction of vent opening by about 30% due to blocking over time. Issue with airflow through unintentional openings if only intentional air-bricks are surveyed. This will give an erroneous assumption in the calculations, underestimating heat loss from void ventilation.
Wind shielding factors (f_w)	0.02 for sheltered, 0.05 for average and 0.10 for exposed locations.	(Williamson, 2006) suggests 0.01 for sheltered; 0.13 for average and 0.18 for exposed locations.	-	f_w may underestimate the wind-driven effect – see Williamson (2006).
Effective wind speed (v)	Average heating season wind speed at 10 m height.	Use 5m/s at 10 m height if unknown (Anderson, 2006).	-	Assumption of airflow in the void by theoretical deduction at 10m height to air-brick level – which adds to uncertainty, particularly as it is dependent on site-specifics (Sequeira et al., 2010) and windspeeds vary significantly.
Make up of below floor walls & thermal conductivity (U_w)	1.7 W/m²K assumed.	2.01 to 3.01 W/m²K (Szokolay, 2008) and for internal solid walls: 2.1 W/m²K (Cook, 2009; Thorpe, 2010).	1.1+±0.2 W/m²K (Baker, 2011) and 0.84-2.52 W/m²K with 1.4 W/m²K as median (Birchall, 2011).	There appears to be a wide range of solid wall U-values, but these U-values are unlikely to reflect those of foundation walls; these are not plastered/pointed and might even be built with variability in construction and workmanship, which would also affect the U-value.

			However this is of internal walls with internal finishes and unlikely to be applicable to sub-floor walls.	The U-value of sub-floor solid walls is unknown and the assumed input could be erroneous. Note that in-situ measured U-values are subject to different analysis protocols, making comparisons difficult and also have associated uncertainties.
Thermal bridging	The floor is considered isolated from walls in the models and the finished floor surface is considered to be the separating plane (BSI, 2009b).	Unknown	ISO-13370 refers to ISO-6946 (BSI, 2007) for calculation of linear thermal bridges with more complex thermal bridges to be calculated by ISO 10211 (BSI, 2009a). Calculations nevertheless rely on assumed material thermal properties and dimensions.	
Floor conductivity & 'joist to floor board ratio'	Conductivity (k) softwood: 0.15 W/mK and k hardwood 0.15 W/mK	Softwood k= 0.13 W/mK and for hardwood 0.18 W/mK. Default joist proportion of 11% (Anderson, 2006).	No large scale surveys to verify joist proportion for the pre-1919 stock, but is similar to cases studied.	Assumptions include whether timber is soft or hardwood, absence of noggings and thermal conductivity. Timber is a varying material and its thermal properties depend on species, its moisture content and density (Anderson, 2006). Proportional calculations of joist presence as a proportion of floor area can be done, based on actual measurements.
Natural convection and radiation	Included in the surface thermal resistances of Ug, Uf and Uw, but unclear if this captures the radiative and natural convective components sufficiently accurate.	-	Natural convection is considered to be a minimal influence (Harris, 1997) but not well-characterised. Given the prevalence of forced convection in the void, convective airflow may be a small driver in certain void locations.	
EXCLUDED INFLUENCING FACTORS				
Forced convection stack-effect & floor airtightness	Floor airtightness is excluded from floor heat-loss models, yet this influences ventilative stack-driven heat-loss. Stack-effect will be determined by floor airtightness but also house airtightness/leakage.	-	Stack-effect through gaps and cracks in the floor was observed by for example (Hartless, 1996; Hartless, 1999; Lilly, 1998). Wind-driven sub-floor airflow may affect thermal surface resistances (Harris, 1983) leading to overall increased heat loss through floors; stack-driven airflow could have similar effects but this is not characterised at present. In-situ U-value measurements also exclude stack-effect. (RdSAP for whole-house heat loss estimation includes assumptions about ventilative heat loss through suspended floors and assumes that buildings built with suspended timber floors pre-1975 in England, Wales and Scotland and pre-1977 in Northern Ireland will have unsealed suspended timber ground floors (i.e. with gaps and cracks, assumed 0.2 ach-1) and sealed floors (0.1 ach-1) after this period (BRE, 2014), p.179); its accuracy is unknown.	
Wind direction & relationship to air-brick location	Excluded, yet increased wind-driven ventilation was observed in the void where air-bricks are facing the prevailing windward side (Hartless, 1994).			
Sleeper wall presence	Sleeper walls and any heat loss through them are excluded; party walls are also excluded from exposed perimeter calculations.		Sleeper walls may lead to increased or reduced heat loss from the floor in depending on location and whether insulated or not (acts as additional thermal bridge when insulated) and may alter or obstruct airflow patterns (Harris, 1994).	
Others	Uninsulated services such as hot water and radiator pipes are excluded, yet would condition the floor void in certain locations and affect heat loss. It is unclear how other constructions in the void might affect air flow and hence heat loss and the effect of seasonal ground thermal mass storage is also poorly characterised for suspended ground floors.			

Table 44. Identified assumptions and excluded inputs in the ISO-13370 model - adapted from Pelsmakers (2012)

Appendix 2.B: Floor insulation materials - summary table

Insulation material	Notes (related specifically for use in suspended timber ground floors
Closed cell insulation; e.g. polystyrene (EPS & XPS), polyisocyanurate (PIR), polyurethane (PUR)	Considered inappropriate for suspended timber floors by EH (2010), as it is vapour impermeable, and may increase condensation risk. Installation is more difficult as usually rigid boards which need to fit between irregular joist spacings. Usually they are cut deliberately short and gaps are filled with sprayed foam. Older uPVC electricity cables can decay and cause a fire-risk when in contact with EPS insulation (Tait, 2010).
Fibre glass and mineral wool	Most commonly used; cheap and easy to install; allows some vapour movement; when wet its thermal performance is reduced and may break down (EH, 2010) and as witnessed by Lstiburek (2008). Usually installed in netting in between joists; though as the fibre is air-permeable, might benefit from being suspended in an airtight, vapour open membrane instead of netting. Might provide essential nutrients for timber rot/mould growth, particular dry rot (Douglas and Singh, 1995).
Natural fibres; e.g. sheep's wool, hemp, cellulose, woodfibre	Considered most appropriate for suspended timber floors by EH (2010) as these materials are moisture permeable, reducing void condensation risks. Moisture can be absorbed and released, though is at risk of decay over a longer time period. Moth infestations can occur in sheepswool insulation and may therefore not be suitable in floor voids (May, 2013), where insects can easily access the void through the airbricks. The desirability of high vapour permeable insulation materials is that they help regulate any build-up of humidity in the void and can release this back to the internal spaces; likewise spillages from internally in the room. Instead of netting, breathable membranes are usually used to support the insulation.
Reflective foil/radiant barriers	Thin layers of reflective foil which can be placed under or above floor joists. Reduces vapour permeability; vapour and air-permeable around the edges (Cox-Smith, 2008). Found to collect dust (losing its reflective capacity) and disintegrate over time (Tait, 2010).

Table 45. Floor insulation materials summary table

Appendix 2.C: Summary of the main fungi found in buildings

Timber decay does not generally occur below 22-24% WMC, often lowered to 20% as a safety measure (Ridout, 2001) (or equivalent to around 90% RH (EH, 2010)). However timber decay might not occur below 28-30% WMC, which is associated with relative humidities of at least 95% (EH, 2010).

The lower the WMC, the less susceptible to decay (Oliver, 1997) and is ideally below 15% WMC (Ridout, 2001) (or <75% RH (EH, 2010)). This is also the threshold to minimise wood-boring insects infestations, which is greater in decayed timbers (Oliver, 1997, EH, 2010), though wood boring beetles can survive in 12% WMC (Ridout, 2001)(or RH of about 62% (EH, 2010)).

Characteristics and optimal growing conditions for the main building timber-decaying fungal organisms (dry rot and wet rot) as well as non-timber decaying moulds are summarised in *Table 46.* All airborne spores can be a health hazard but in all cases remedy and prevention of moisture build-up and water penetration eventually kills the fungus (Ridout, 2001, Oliver, 1997) and reduces occupant exposure. From summary *Table 3.* it can be noted that wet rot requires higher moisture thresholds, while for moulds, thresholds for growth are lower. At very high RH (> 97% RH or wet materials) bacteria also cause smell and health problems similar to mould fungi (Viitanen et al., 2010).

Dry rot (Serpula lacrymans, wood-rotting fungi	• One of the most common fungi in buildings in the UK (Douglas and Singh, 1995). • High moisture conditions can occur with inadequate floor void ventilation (Oliver, 1997) • Optimal and rapid growth at 21-23ºC with WMC of 30-40% (Douglas and Singh, 1995, Oliver, 1997), requiring >90% RH at minimum >20ºC (Ridout, 2001). It can grow at lower thresholds, though decay will be slow (Ridout, 2001). Others found ideal RH of 99% (or 26-30% WMC)(Ridout, 2001). • Its food source is timber or other cellulose based materials (Douglas and Singh, 1995) and it needs a source of calcium, which is present in damp cement/lime mortar and in plaster (Ridout, 2001, Douglas and Singh, 1995), and other organic material, such as rock or glass wool insulation (Douglas and Singh, 1995), commonly used in buildings (EH, 2010), including floors. • It requires stable, unchanging environments to thrive in and is therefore often limited to the damp zone; while remedying the source of moisture makes the fungus dormant and eventually kills it, it could take up to a year or longer at lower temperatures before the fungus is killed (Ridout, 2001). • Fungal spores can remain viable for several years (Ridout, 2001). • If conditions allow, dry rot can colonise other areas and grow through brick, but needs high RH for active growth (Ridout, 2001). • Chemical treatments do not remain effective in continuing damp conditions so remedying the dampness is a priority (Ridout, 2001).
Wet rot, includes 'cellar rot' (Coniophora puteana, wood-rotting fungi)	• Occurs when timber is continuously damp, for example where it is supported by wet brick work or soil (Ridout, 2001) and is common in poorly ventilated floor voids (Oliver, 1997). • Optimal growing conditions are 20-25ºC with WMC above 30% (Ridout, 2001, Douglas and Singh, 1995) (i.e. ~100% RH); with optimal WMC of 50-60% (Oliver, 1997). • Does not require calcium for growth.
Moulds (non-wood-rotting fungi)	• Mould fungi do not tend to decay timbers but have superficial growth on surfaces and may stain surfaces (Ridout, 2001) • Typically grows on timber in conditions of >70% RH (Oliver, 1997). • Mould can grow on EPS and mineral wool insulation during long-term exposure to RH >97% (Viitanen, 2007).

Table 46. Summary of the main fungi found in buildings.

Appendix 2.D: Floor void moisture management solutions

Some possible solutions to floor void moisture management are summarised below from literature:

- Moisture problems in insulated Californian floor voids were remedied with the introduction of ground covers (Flynn, 1994) while (Werther, 2010) also observed 10% to 15% reductions in summer void RH in a Leipzig test cell after introducing a ground cover.
- Ground insulation was found to reduce moisture build-up in insulated floor voids due to the wall and ground thermal mass preventing the cooling of summer air in the void, reducing high void RH (Matilainen, 2003, Airaksinen, 2003, Kurnitski, 2000) in Finland; (Samuelson, 1994) in Sweden and (Werther, 2010) in Germany. An increase in winter RH is likely: the floor void loses the beneficial thermal mass effect in autumn and winter, creating a yearly void condition similar to the external environment (Samuelson, 1994), though summer temperatures are lifted by a few degrees and this might often be enough to bring void RH to a safe level (Kurnitski, 2000).
- Insulation of foundation walls might not be effective in balancing summer moisture build-up in insulated suspended ground floors in Finland (Matilainen, 2003, Airaksinen, 2003). Heat transfer in summer might help increase summer void temperatures (Matilainen, 2003) rather than act as a heat sink, but this is likely to depend on the type of wall and its thermal mass capacity.
- To avoid surface condensation and mould growth, (NBS, 2013) requires all areas of a new or upgraded floor to have a U-value of 0.70 Wm^2K^{-1} or better (i.e. less), with 0.25 Wm^2K^{-1} as target U-value. However, suspended ground floor U-values may need to be balanced against void moisture build-up: air temperatures in the floor can be raised by reducing floor insulation as this increases the downward heat-flow, raising void RH, as observed by (Samuelson, 1994) and (Airaksinen, 2003). However, in winter, this is likely to be associated with increased energy use and thermal discomfort (Airaksinen, 2003). (Airaksinen, 2003) observed that floors with a typical U-value of 0.2 Wm^2K^{-1} had average 2ºC colder void air temperatures and void RH almost 10% higher than floors with 0.4 Wm^2K^{-1} U-value.
- Floor voids can also be heated mechanically to keep RH within acceptable limits and can be controlled to kick in when 70% RH is exceeded (Samuelson, 1994) or 75% RH as suggested by (Airaksinen, 2003). While this may prevent floor void mould growth and in turn transferral into internal spaces, this is at the expense of increased energy use and incurs capital and running cost. This is probably best combined with sealed void ventilation to prevent humid air entering and heat-loss.
- Increased ventilation in the summer only works to dry the floor void if it removes more moisture than it adds due to the increased evaporation rate of ground moisture and additional high RH of the external summer air being brought into the void (Kurnitski, 2001) (Kurnitski, 2000, Airaksinen, 2003).

Appendix 3.A: Literature sources

Research topic	Main sources	Notes
1. Victorian dwellings and their construction	Little academic work; mostly grey literature.	
2. building physics floors, incl. models	BRE, CIBSE, ISO-13370, RdSAP, building physics handbooks and academic papers, e.g.	Limited number of academic papers on suspended timber ground floors; academic papers and grey literature
3. in-situ heat-loss measurements and protocols	Main protocols ISO 9869, ASTM 1046 and 1055, CEN En 14949 and industry research such as Historic Scotland, Baker, EST, BSRIA, BRE , ASTM and papers utilising in-situ measurements and reviewing techniques.	academic papers and grey literature; very limited for suspended timber ground floors
4. floor void ventilation	Literature on suspended ground floor void ventilation was available mostly from AIVC conference proceedings.	
5. insulation of suspended ground floors	Efficacy and methods of insulation is mostly available from industry bodies such as EST, BRE and test-cell experiments (Werther, 2010, Harris, 1997) or modelling (Matilainen, 2003)	Mostly grey literature
6. timber rot	Timber rot handbooks (biology of fungal growth) and industry (mostly building surveying) guidance. Some academic papers on modelling of timber rot in Finnish suspended floors.	Papers and grey literature
7. Thermal comfort	Thermal comfort literature is vast and therefore was mostly focused on the appropriate ISO standards and on papers related to floors and thermal comfort, of which there are a limited number of papers, pre-dating the 1980's.	Given the timescale and focus of this PhD, no extensive critique of thermal comfort theory or research methods is provided, however is acknowledged.
8. Statistics	Few sources are directly applied to our discipline hence advice from statisticians was also sought; main source was Taylor (1997) and Squires (2001)	
9. Experimental research design	Mostly books on experimental research design –grey literature.	

Table 47. Main literature review sources

Appendix 3.B: Theory testing & theory building

Dimension of the 'problem'	Formulation hypotheses (H)	Detail/options	What and how to measure?	Cases Required
THEORY TESTING (deduction) 1. [illegible] 2. [illegible] 3. [illegible]	**H1. There will be a large observed spread of U_f-values across the uninsulated floor.** **H2. There will be increased perimeter U_f-values observed compared to locations further away from the external wall (i.e. the non-perimeter zone).** **H2a. This will be observed both for insulated and uninsulated floors, albeit reduced for the latter.**	[illegible]	[illegible] **Heat-flow measurement and pre/post intervention study:** [illegible] **Confounding factors in the field:** [illegible] **Thermal comfort:** [illegible] **Floor void conditions:** [illegible]	**Test method first in an Environmental Chamber** [illegible] **Final unoccupied house and characterise floor heat-flow at high resolution:** [illegible] **Unlikely to obtain large sample of insulated and uninsulated floors to measure floor void conditions:** [illegible]
THEORY BUILDING (induction) 4. [illegible] 5. [illegible] 6. [illegible]	**H3. There will be increased thermal transmittance observed with unsealed airbricks compared to sealed airbricks and this effect will be proportionally smaller in insulated than in un-insulated floors (H3a).** **H4. There will be a reduced spread of U_f-values observed for the insulated floor compared to the uninsulated floor** **H5. There will be a significant decrease observed in thermal transmittance after insulation installation; insulation will also be observed to improve dwelling air tightness (H5a).** **H6. Post-insulation it will be observed that thermal comfort is improved.**	[illegible]		
	Interlinking/confounding factors/other issues? [illegible]			

Table 48. Summary of dimension of the problem and case study selection, adapted from (Pelsmakers, 2013).

Appendix 3.C: In-situ measuring protocols summary table

In-situ measuring – summary protocols	ISO 9869-1 In-situ measurement of thermal resistance and thermal transmittance.	NEN-EN 12494 Building components and elements – In-situ measurement of the surface to surface thermal resistance	C1046 and ASTM C1155
Origin/status	Internationally agreed & approved (1994 & 2014)	Netherlands, does not replace ISO 9869 draft/design status (1996/97)	USA (2007) standards
Applicability?	Components with opaque layers perpendicular to the heat flow, without significant lateral heat flow. Implies use of ambient air temperatures on each side of the elements.	For all flat materials, sufficiently homogeneous, without significant lateral heat flow or moisture transfer. Use of surface to surface measurements.	Suitable for opaque building elements (wall, roof, floor & door), though windows also listed.
	To be undertaken by qualified, knowledgeable people. Not intended as a high precision method.		
Thermometry instruments + Calibration	Minimum 1 temperature sensor on each side of the element. Calibration to achieve accuracy of +/-2% between a pair of sensors. Temperature sensor accuracy < 0.1K.	Temperature sensor accuracy < 0.1 K, or 1% (the less severe of the two limits). Incorrect placement error ≤ 2% difference in temperature across the element.	Calibration only acceptable if carried out to ASTM C1130: Standard Practice for Calibrating Thin Heat Flux Transducers.
Heat flux sensor instruments + Calibration	Must have a low thermal resistance with high sensitivity to allow for the lowest heat flow rates measured. Total HF sensor accuracy +/-5%. Sensors should be calibrated minimum every two years, carried out at a representative temperature on a building material.	Calibrated to give an accuracy of < 0.5%. Where calculating the average U-Value this should be done with an uncertainty of less than 0.1%. This is onerous and unclear if achievable by most equipment: standard calibration gives +/-5% accuracy.	
Heat flux (HF) sensor installation	Infrared thermography recommended for sensor placement (ISO 6781)		
	Sensors, with colour + emissivity the same as the element surfaces, should be placed to achieve a representative result, away from cracks, thermal bridges or sources of heating/cooling/fan draughts or other sources of error.	Very specific and onerous. In addition to avoiding solar radiation, cracks and thermal bridges, measurement of a 1m2 solid brick wall requires a 'guard' distance of 300-475 mm from corners depending on observed element, windows and beams to have < 1% error.	To avoid solar radiation, curtains to be closed. Sensor's thermal resistance to be < 1% increase of element resistance. Presence of lateral heat flow requires top/middle/bottom placement of sensors on element.
	Measured area to be representative of element. Thin layer of thermal paste for good surface contact.		
Thermometry installation	For U-values air temperatures must be used and for conductance/resistance, surface temperatures. To be mounted under or in vicinity of the HF sensor.	Surface temperature measurements are recommended. Where in-homogeneous surface temperature, radiation shielded air temperature sensors to be used. Minimum 9 surface temperature sensors surrounding the heat flux measurement area, with another 12 in the 'guard' area. Surface temperature sensors placed under, on top of heatflux sensor or next to it.	Close match of sensor with element's absorptance, emissivity and colour, which can be achieved with coloured masking tape on smooth surfaces. On rough surfaces, use of gel tooth paste or petroleum jelly to ensure good contact and reduced error.

	Surface temperature sensors colour + emissivity to be the same as the element surfaces and to be mounted with good surface-contact, including the first 100 mm lead wire contact. External sensors opposite the internal HF sensor.		
Data acquisition method	Recording interval typically 30-60 mins, averaged from smaller intervals	Indicative recording interval: every 10 minutes to 1 hour	Sampling minimum every 5 minutes and averaged in intervals of ≤60 minutes
Time requirement	Min. 3 days with stable temperatures, otherwise ≥7 days. For lightweight elements, only night-data to be used. For heavyweight elements, test to be carried out in multiples of 24hrs.	Min. 3 days (or 3 nights for lightweight elements) and the test can be stopped if R-values obtained after each night do not differ by more than 2%, otherwise continue. For all other elements, test to be carried out in multiples of a full 24hrs.	
	Specific tests to be undertaken, which require that the U-values compared in the data set are within +/- 5% (ISO) or 2% (CEN) of the value obtained 24hrs prior in test 1, and if the first 2/3rd of the data is within 5% (ISO) or 2% (CEN) of the last 2/3rds of the data for test 2. This is to account for any thermal mass delay effect. Correction factors can be applied if tests are failed but are based on material and construction assumptions – see standards for more detail.		
Error analysis & accuracy	Total random uncertainty of +/- 14% to +/- 28%.	Excludes temperature sensor errors (+/- 0.5 K), HF thermal resistance; No correction required if <0.05 m²K/W.	Report to include an estimate of the precision and bias of the measurement. Only protocol to estimate lateral heat flow error of +/- 28% (ASTM, 2001a)
Reporting protocol	Result obtained is an 'estimate of the U value' and final reporting to include details of measured elements, measurements, analysis method and results.	The standard contains specific guidance on the preparation of a final report, and this to include details of elements, measurements and method of analysis.	Detailed requirements, including detailed description of measured element and instruments, weather, HVAC system, occupancy, purpose, test duration, criteria and reasoning behind this. Discussion of averaged results with an estimate of the precision and bias of the measurement.
Other?	No heating equipment or methodology specified. Comparison of in-situ to Modelled or calculated R-values are considered to be significantly diverging if > 20% and both models and measurement conditions need to be evaluated.		

Table 49. In-situ measuring protocols summary table

Appendix 3.D: In-situ measuring protocols uncertainty summary table

Type of uncertainty	Description/detail (random errors unless otherwise stated)	Estimated error?
Data analysis method	The average data analysis method is based on steady state analysis, while its inputs are measured under dynamic conditions (McIntyre, 1985, IEA, 2012), The Average Method assumes dynamic effects are minimised if taken over a sufficiently long period. Dynamic effects include solar radiation, wind velocity (which changes the surface resistance) and thermal mass and non-perpendicular airflow. The uncertainty will depend on measuring conditions (see below) but may be minimised by measuring in winter time and over a sufficiently long enough period or by undertaking Dynamic Analysis. CEN (1996) defined a '**Non steady state error' at ± 2%.**	± 2% (CEN,1996)
Measuring conditions	Unknown errors from **environmental influences** such as wind velocity, draughts near windows and from open windows; direct solar radiation & radiant heat sources. These errors can be minimised by screening & closing curtains (ISO, 1994, IEA, 2012, McIntyre, 1985, Cesaratto et al., 2011). Solar radiation & wind velocity, if measured, may be included in a dynamic analysis method,	-
	Deviations from attempted measurement to actual temperatures being measured. For example, furniture location and inhomogeneous spread of internal temperatures affecting temperature measurements; vertical stratification. Ambient to ambient temperatures, required for the determination of U-values and total thermal resistance, cannot be directly measured. Uncertainty will depend on how the ambient temperature is defined and usually air temperatures are used instead (BSI, 2014). Placing additional surface and air-temperature probes around the sensor is beneficial to deduce ambient temperature; as recommended by ASTM (2007a). Due to limited resources and practicalities of in-situ work, this is often not possible. Siviour (1982) recommends internal sensor within 0.5m from the face of the wall under measurement; others within 10 mm to a few centimetres from the sensor (BRE, 2014, Birchall, 2011).	±2% (CEN,1996) or ±5% (inferred from ISO-9869 (BSI, 2014)
	Heating method: unquantified uncertainty, but method of heating affects estimated U- and R- values due to possible temperature fluctuations and inhomogeneous spread of temperatures. Emery (2007) noted that small changes in local air temperatures, such as those from air-circulation from fans affect measured heat loss.	-
	Changing moisture affects the thermal properties of construction elements (Anderson, 1984, CEN, 1996, Rhee-Duverne, 2013); uncertainty due to redistribution of moisture typically 5% (CEN, 1996).	±5% (CEN,1996)
	Different environmental conditions (such as variations in temperature). Can be minimised by measuring over pro-longed periods; reducing internal temperature variations and by using Dynamic Analysis Methods. If ISO tests are met, error can be < ±10% of the measured value (ISO, 1994).	± 10% ISO-9869 (BSI, 2014)
	Deflection error: The presence of the heat-flux meter changes exactly that which is attempted to be measured**,** disturbing local air- and heat-flow due to sensor placement (Cesaratto et al., 2011, Trethowen, 1986, Childs, 1999). Can be large for sensors in soils. Placing a heat-flux sensor on a surface inherently disrupts the characteristics of what is being attempted to be measured (Childs, 1999), leading, for example, to random deflection and reflection errors.	± 2-3% ISO-9869 (BSI, 2014)
	Unknown researcher and occupant influence (systematic and/or random)	-
	Assumed perpendicular heat-flow only on the observed element (Cesaratto et al., 2011): reality may have multi-dimensional heat-flow due to thermal bridging, lateral conduction or convection and vertical temperature gradients. Error could therefore be large but usually excluded from error propagation as unknowable. The effect could be averaged out by a sufficient number of sensor sites (ASTM, 2007b, ASTM, 2007a). See also below thermal bridging.	± 26% (ASTM, 2007a)

Construction element (in)homogeneity	**Thermal bridging or local inhomogeneities** , such as (variable) mortar joints (Siviour, 1994, Byrne et al., 2013), presence of airgaps, air movement and hidden services (Doran, 2001). The measured surface needs to be representative of the entire construction element under observation. Can be minimised by using IR thermography for representative location with minimal lateral heat flow (ASTM, 2007a, ISO, 1994, CEN, 1996).	-
	Imbalance in heat-flow for non-homogenous elements (systematic)	± 4% (CEN,1996)
Instrument error	**Correction factor to avoid systematic error for thermal resistance of heat-flux sensor itself: addition to measured R:** Thermal resistance <6.25 x 10^{-3} m^2k/W (Hukseflux).	
	Calibration errors of heat flux sensors (systematic)	± 2% (CEN,1996)
	Calibration error of temperature sensors (systematic)	± 1% (CEN,1996)
	Heat-flux sensor instrument precision. Can be as large as ±5% to - 15% for soil measurements (Hukseflux).	±5% ISO-9869 (BSI, 2014) or ± 4% (CEN,1996)
	Temperature sensors instrument precision–depends on specification. Aim to be as accurate as possible, preferably 0.1ºC in measuring conditions	±0.1°C – 0.5ºC
	Surface temperature uncertainty: 0.5ºC; 5% on 10ºC. Greater for inhomogenous elements (CEN,1996).	±5% or 0.5ºC (CEN,1996)
	Reading temperature sensors (systematic)	± 0.5ºC (CEN,1996)
	Accuracy of data-logger and wire resistance.	± 0.5% (CEN,1996)
	Sensor reflection/absorption. Spectral differences/influences: heat-flux sensors have a different emissivity than the surface of the observed element (Cesaratto et al., 2011)	± 6% (ASTM, 2007a)
	Edge heatloss error (systematic)	± 1% (CEN,1996)
	Sensor contact: Good contact is required between heat-flux sensor and the surface of observed element. In soil, contact with soil is tricky so errors can be large hence averaging of two sensors next to each other is recommended (±15%, (Bos, 2012)). There will be uncertainty due to this and due to additional thermal resistance of any application method used (Siviour, 1982, McIntyre, 1985, ISO, 1994). Thin layer of silicone grease was found most accurate by Siviour (1982). Other methods may be less accurate: taping; embedding in Blutac with possible decreased contact from double sided adhesive tape (89%) and pressure against sensor with low conductivity rod (83%) (Siviour, 1982). Others (Stevens, 2013) use silicon grease on the sensor with a thin layer of plastic to protect building surface, however it is unclear whether this affects contact.	± 1% (ASTM, 2007a) or ±5% ISO-9869 (BSI, 2014)

Table 50. In-situ measuring protocols uncertainty summary table

Appendix 3.E: Summary of (dis)advantages of thermal chamber versus (un)occupied dwelling studies

Intervention study	Limitations/advantages
Intervention study: test-cells & environmental chamber	While test-cells can provide invaluable insights in floor heat-loss and heat-loss reduction measures as undertaken by Harris (1997); it is difficult to replicate real in-situ conditions, such as ventilation air flow and thermal mass as well as perimeter to floor area ratios; variables thought to significantly contribute to actual floor heat-loss. Test-cells will not answer the research question for in-situ situations, but may nevertheless provide useful insights. The Energy House at Salford University is a reconstructed 1920's house in a thermal lab; controlled experiments can be undertaken, as well as the suitability of in-situ measuring techniques and analysis methods can be tested in a more controlled environment. Advantages of the Salford EH: 24hr controlled environment with steady state-like internal and external environmental conditions, minimising influencing variables and reducing measurement time, while maximising ΔT between the internal and external environment. It is an unoccupied environment so high resolution monitoring is possible. However the Salford EH does not replicate a real house (as discussed in Chapter 4), and excludes seasonal patterns as the external chamber is kept at winter temperatures for most of the year. Construction discrepancies include that the house stands on a concrete plinth of 280 mm on top of a concrete insulated slab, are 190 mm deep, allowing just 50-70 mm underneath the joists for air to flow in the subfloor void and this is likely to restrict airflow from the front of the house to the back; no airbricks to the back of the house; an open airbrick to the neighbouring house; part of the floor has air-gaps between the floorboards, while the rest does not.
Intervention study-occupied house	The benefit of in-situ measuring means that actual conditions are measured and reflected in the measurements. Case studies have been found where occupants are planning to undertake floor insulation. This has of benefit that the researcher does not need to find a commercial partner to undertake the intervention measure. However often these are combined with other fabric improvements; occupants may change behaviour or interfere with what is being measured, making floor heat-loss analysis more difficult due to different changing variables and possible confounding influences (such as wall insulation affecting heat-loss through the floor perimeter). It may not be clear whether observed changes before and after insulation are true changes or not. A larger sample may therefore be required to be meaningful, but each intervention measure is likely to substantially different from another, as would be the existing floor construction and geometry. However in-situ floor measurements in an occupied house will limit data collection to a limited number of suitable locations, specific to each dwelling layout and use of the room/furniture layout. Reliance on occupant heating pattern may provide insufficient ΔT between inside and outside; and where also uninsulated radiator pipes run under the void, influencing that what is being measured. (and which will be another changing variable post-retrofit measurements). Relies on measures being installed in winter with 2-3 weeks pre-installation to enable measurements and 2-3 weeks post installation.
Intervention study - unoccupied house	This may utilise the benefit of both the thermal lab and the occupied dwelling option, while minimising the limitations of both. An unoccupied dwelling can be heated to a set-point temperature pre-and post insulation and energy use may also act as an indicator of any heat-loss reduction; the two main variables might be reduced to external environmental conditions (incl. seasonal changes) and the intervention measure. This would enable testing in one house of 2-3 intervention measures; requiring a minimum 6 weeks during the winter period for one intervention; and 3 months for up to 3 interventions. Could be combined with blower door tests. Energy use: only that of the measuring instruments and the heat input from thermostatically controlled electrical heaters to maintain a constant internal temperature; creating significant ΔT. The main limitation is the difficulty of finding an unoccupied house for an extended period.

Table 51. Summary of (dis)advantages of thermal chamber versus (un)occupied dwelling studies

Appendix 3.F: Information sheets and informed consent

STUDY 1

Initial Project letter, followed by additional info letter and consent form below.

Why are Ground floors in victorian houses so cold?

Millions of britons live in poorly insulated Victorian houses. As many of them know, not only the houses can be cold, the floors can be especially cold and draughty, and not just in winter! A cold floor can be much more than just a nuisance though, it can have a serious cooling effect on the house. People might find that cold floors increase their heating bills, which, in these times of economic hardship, might severely affect them financially.

My research aims to investigate heat loss through ground floors, so we can understand better what we can do about it without causing a huge disruption or expense to the occupants. To do this, I am looking for 4 to 5 victorian houses which:

- have timber suspended ground floors
- ideally original timber floor boards
- and occupants are happy for me to 'measure' how cold the floors are for a period of 3 weeks leaving a number of heat sensors in their homes. I would need to meet with you 3 to 4 times in this period.

This research is intended as a pilot study to base future research on, particularly related to insulating these floors in an easy and cheap way, without damaging the structure; and preferably without lifting the floor boards.

The research is carried out by UCL (a state university) and is not being funded by any commercial organisation and is only for research purposes. All results are confidential!

I am looking for houses in the vicinity; this is because I am looking for houses similar to each other; with a similar local climate and to limit traveling time (I live in N17).

The research project will take 3 weeks, somewhere between February and April. You can however at any point in time decide to withdraw from the study.

If you think you could be interested, please contact me at 07905696333 or via email

sofie.pelsmakers.11@ucl.ac.uk

and I will send you more detailed information about how the measurements will take place.

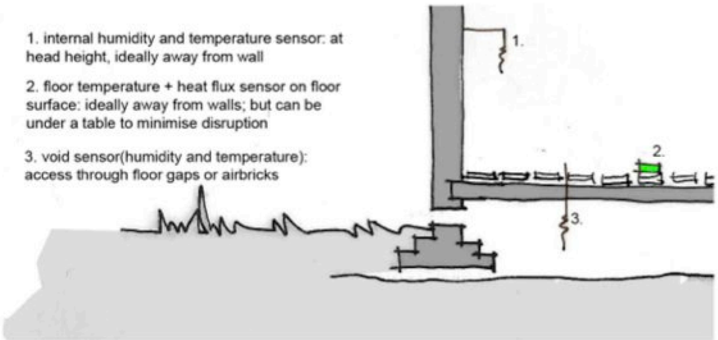
Why are Ground floors in victorian houses so cold? – Additional info

My research aims to investigate heat loss through ground floors, so we can understand better what we can do about it without causing a huge disruption or expense to the occupants.

If you agree to take part in the research; this is what it will involve:

1. Firstly, we should probably meet to make sure you are happy to be involved!
2. Then an infrared image will be taken of your ground floor, and around wall and floor junctions. This will help me to decide where to place the sensors. (for example, the sensors should be away from heating pipes under the floor boards, because otherwise I would be measuring the radiator's heating, not the heatloss!)
3. I will probably place the floor sensors on a second visit. These sensors will be located in discussion with you so that they are not in the way of your daily activities. See diagram below.
4. All of the sensors need to stay in place for 3 to 4 weeks, and will be put in place with bluetack and tape, which leave no residues on the floor surface. Putting in place may take around 2 hours.
5. Once the sensors are in place, I will return after 48 hours to download some data, just to make sure everything is working fine and then I will return on a weekly or fortnightly basis to download the data. (around 1hr max.) Any meeting will be scheduled at your convenience.
6. **The total time required is estimated at around 8 hrs over 3-4 weeks**

Diagram of what will be measured where



How much nuisance will it really be?

Aside from the short installation and regular collection intervals as agreed with you, there will be one round disc - the size of a jam-jar lid - located on the floor. Ideally these sensors sit away from walls and radiators and furniture, but the middle of the room is not a good location to place a sensor as it will be a nuisance to you. So, we might have to locate the sensor under for example your dining table.

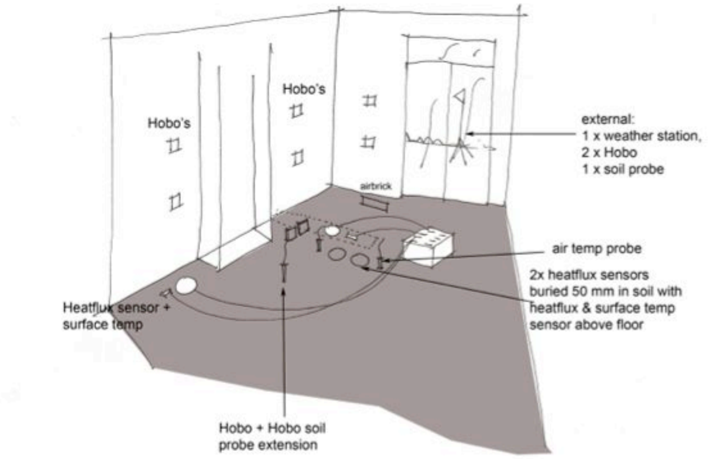
What else?

- I may ask your permission to take digital photographs of installed sensors
- **Your participation is voluntary and you have the right to withdraw at any time**
- Any information obtained will be anonymous and will not be availble in the public domain and is just for academic purposes

Who will undertake the research and when?

- The research will be undertaken by a Postgraduate researcher, Sofie Pelsmakers, from University College London who has lived in N17 since 2007. I originally trained as an architect, taught at University of East London and am now studying again. My profile can be found on http://www.linkedin.com/pub/sofie-pelsmakers/17/5a3/12.
- *The research project will take 3-4 weeks, somewhere between February and April.*
- My contact details are 07905696333 and email sofie.pelsmakers.11@ucl.ac.uk

Approximate diagram of what will be measured where



How much nuisance will it be?

- Some time to install and collect the equipment with weekly collection intervals as agreed with you.
- There will be two round discs - the size of a jam-jar lid - located on the floor. This is connected with a wire to a box. These connections or sensors should not be moved for the 4 week period, so you will have to clean around them. We will make sure any wires are not a trip hazard and run along wall edges. These will probably be taped to the floor.
- I may ask your permission to take digital photographs of installed sensors
- I will need to do a detailed survey of the floor, including airbricks, gaps between floorboards etc and will draw up a ground floor plan. These plans will be shared with you and you will be provided with a copy.

What are the possible benefits in taking part?

You will contribute towards knowledge in heatloss in victorian houses and how this can be resolved. Research findings will be shared with you.

What else?

- **Your participation is voluntary and you have the right to withdraw at any time**
- Any information obtained will be anonymous and will not be availble in the public domain and is just for academic purposes

Who will undertake the research?

- The research will be undertaken by a Postgraduate researcher, Sofie Pelsmakers, from University College London who has lived in N17 since 2007. I originally trained as an architect, taught at University of East London and am now studying again. My profile can be found on http://www.linkedin.com/pub/sofie-pelsmakers/17/5a3/12.

As discussed before I'd like to thank you for agreeing to take part in this study in your home. By completing and returning this form, you are giving us your consent that the data collected will only be used for the purposes of this research project and not transferred to an organisation outside UCL.

Any personal information or form of identification will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.

If at any point you have any concerns about the way in which this study has been conducted, you can contact the UCL Research Ethics Committee on 0207 679 7844.

Thank you for taking the time to read this information sheet and for taking part!

Sofie Pelsmakers
The UCL Energy Institute
Central House
14 Upper Woburn Place
London WC1H 0HY
sofiepelsmakers@yahoo.com
07905696333

You are being invited to take part in a research project. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

What is the purpose of my study?
My research aims to investigate heat loss through ground floors, so we can understand better what we can do about it without causing a huge disruption or expense to the occupants.

What will it involve?

1. Sensors will be placed on the floor and wall surfaces of one room, as well as in the sub-floor void. A weather station will be located in your garden and a sensor to measure ground tempertature outside and in the sub-floor will also be located. A total of 20 sensors will be placed.
2. The sensors will log temperatures and in some cases relative humidty and heatlosses.
3. The sensors need to stay in place for 4 weeks, and will be put in place with bluetack and tape, and some silicon for two floor sensors, which will leave no residues on the floor surface. Putting in place may take around 2 hours.
4. Some sensors will be connected to a box, which is connected to a modem and antenna. This allows for remote downloading of data. One electrical plug will be required for this.
5. Once the sensors are in place, I will via the modem check within 48 hours to make sure everything is working fine. If it is not, I will need to return to check the equipment, otherwise I will return on a weekly basis to download the data. (around 1hr max.) Any meeting will be scheduled at your convenience.
6. The monitoring will start on March 10th and is due to finish around April 7th. There may be the opportunity to leave some of the sensors for a longer period should you wish to agree to this. (This will be discussed separately)

Floor heatloss monitoring – Consent Form

I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐

I agree to take part in the study ☐

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason. ☐

Name of participant ……………………………………………………………

Date ……………………………………………………………

Signature ……………………………………………………………

Appendix 4.A.: Pairing of U-values

Table 52. lists the 32 paired locations where the mean paired U-value overlapped with the overlapping error margin of the whole floor U-value, i.e. between 0.75 and 0.91Wm^{-2}K^{-1}. Only one pairing combination (location 1 and 9 along the perimeter (and above airbricks), marked in red) lead to an exact match with the whole floor U-value.

Location 1	Location 2	U_mean (Wm^{-2}K^{-1})
HF1	HF7	0.75
HF1	HF8	0.77
HF1	**HF9**	**0.83**
HF1	HF12	0.88
HF2	HF8	0.77
HF2	HF9	0.82
HF2	HF12	0.88
HF2	HF13	0.90
HF3	HF9	0.79
HF3	HF12	0.84
HF3	HF13	0.87
HF4	HF9	0.77
HF4	HF10	0.89
HF4	HF12	0.82
HF4	HF13	0.85
HF4	HF14	0.89
HF5	HF10	0.86
HF5	HF12	0.80
HF5	HF13	0.82
HF5	HF14	0.87
HF6	HF9	0.80
HF6	HF12	0.85
HF6	HF13	0.88
HF7	HF8	0.79
HF7	HF9	0.85
HF7	HF12	0.90
HF8	HF9	0.86
HF8	HF15	0.75
HF9	HF15	0.81
HF12	HF15	0.86
HF13	HF15	0.89

Table 52. Pairing of U-values: table lists 32 mean U-value pairs within the error margin of the estimated whole floor U-value 0.83 ±0.08 Wm^{2}K^{-1}; highlighted in red the two paired locations which exactly meet the whole floor U-value.

Appendix 5.A: Research management and ethical considerations - STUDY 4A/B

Several research management and ethical considerations were taken into account for this field study and are summarised below:

- **Informed Consent and risk assessment** were agreed with the home-owner. Interventions were agreed with the home-owner in advance via email; Building Regulations notification or approval did not apply as the improved part was <50% of the ground floor (NBS, 2015).
- **A reciprocal NDA was signed with Downs Energy**: the purpose of this was to enable Downs Energy to test a floor void filling technique typically used for cavity-filling; while also acknowledging the researcher's expertise input.
- **UCL insurance for equipment and third party insurance** were obtained for the duration of the study.
- **Access to the house:** as agreed, the owner was kept up to date of progress on a regular basis via emails and was notified by text message each time the researcher entered and left the unoccupied property; this was typically 2 to 3 days per week, sometimes daily during an intervention study. The department's 'buddy scheme' for lone working was also implemented: i.e. two people were identified and given prior details of site-visits, with approximate arrival and departure times and sending of text messages upon entering and leaving. If the researcher did not text at the expected departure time, the 'buddy' would attempt to contact the researcher and if failure to do so, would alert emergency services (this was however never necessary).
- **Disruption to neighbours was minimised:** neighbours were notified of any building works and suitable times agreed (such as avoiding certain weekdays or times) to minimise noise and other disruption. After the main field study, neighbours were also notified by text message upon returning for data collection as the house was still unoccupied.
- **Sealing of the airbricks** is considered to be risky to the health of the floor and might contribute to structural damage or void mould growth (Oliver, 1997, Burke, n.d., Douglas, 1998b, Douglas, 1998a, BRE, 1991, Singh, 1998). Hence, with approval from the home-owner, airbricks were sealed for short periods only (< 1 week) for the monitoring of heat-flow for each intervention in this condition; airbricks were sealed for a longer period during the EPS bead intervention. In all cases, the floor void conditions (temperature and RH) were continuously monitored in 3 locations which would allow the study to be disrupted if critical moisture levels for mould growth would be exceeded. Void data was transferred wirelessly from below the void to an easily accessible data logger above the floor void to allow void condition checks at every data collection period - at least twice a week - without having to lift the floorboards.

information sheet

Information Sheet Research Study
You are being invited to take part in a research project. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. You will be given a copy of this information sheet.

Title of Project: Measuring heat-loss through pre-1919 suspended timber ground floors, before + after interventions
Researcher's name: Sofie Pelsmakers
Work address: xxxxx
Contact details: Tel: xxxxx email: xxxxx

What is the purpose of my study?
My research investigates the heatloss of pre-1919 floors and what the reduction potential is of certain interventions and the possible unintended consequences of insulating such floors, for example increased humidity in the floor void. I will be undertaking measurements and interventions as described below. Interventions will be agreed with you at prior to undertaking them.

What will it involve?

1. **A detailed survey** will be undertaken of the external and internal territory to undertake a heatloss model. Particular interest is where ground meets walls (up to 1 meter height), and down into the crawl space area, depending on access. The survey can be made available to you upon request.
2. In some cases, **floorboards will be removed** to gain access to the void and – at later stages – to undertake the intervention. Such work will not be undertaken without prior discussion and agreement with you.
3. **Photographs** will be taken of the floor void and of internal or external wall surfaces, but will never show any personal or private effects or any objects or identifiable property. Access to images can be obtained at any time and you have the right to ask any to be deleted.
4. **15-20 heatflux sensors** will be placed on the floor, in the void soil, on the foundation wall and foundation party wall (depending on access) as well as on the external wall to measure heatloss. This is alongside surface temperature measurements; internal, external and void air tempertaure measurements and Relative Humidity as well as external and void windspeeds.
5. The above research will take place in your unoccupied house from December to mid-March or as agreed. The researcher confirms that UCL's **Public Liability Insurance** covers any accidental damage. The researcher will email and/or send a text message (as agreed with you) in advance of entering the property, upon entering and when leaving the property. At all times the property will be left secured as per owner instructions.
6. **The house will be electrically heated** at a typical occupant heating pattern and with frost protection over this 12-14 week period. The electrical heaters will be PAT tested by UCL. Meter readings will be taken periodically and the energy use over the entire research period will be paid for by the researcher. This can be ~ £300 per month and a discussion is required with homeowner how to arrange bill payment.
7. **Initial work** will involve lifting the carpet to place void sensors, followed by heat-loss measurements on the carpet, on bare floorboards (carpet will be removed), and with (**to be confirmed and as agreed prior**) a radiant barrier and full floor insulation between the joists. In between each intervention, airbricks will be closed for a 1 week period to investigate the effect on observed heat-loss, void windspoeds and void RH . Blower door tests are also likely to be undertaken.
8. Due to high-resolution of data collection over a ~ 12-14 month period, it will take several months afterwards to analyse the data, however **the results of the study** can be shared with you once the data has been analysed and they are available. The sharing of results will be done in confidence, until results are published.

How much nuisance will it be?
The whole process will take 2-3 months, with regular (~ twice weekly visits) by the researcher. Your separate approval and agreement will be required prior to any invasive works being undertaken such

as lifting or cutting of floorboards and installing insulation, which will require some additoonal time to review and agree the proposals.

What are the possible benefits in taking part?
By agreeing to allow this study to take place in your unoccupied house, you will contribute towards knowledge of heatloss and floor conditions in existing houses and solutions for insulating them. Research findings can be shared with you upon your request. If the researcher finds any suggestion of evidence of an unhealthy floor or any other issues during the period, this will be shared with you, although this is not a professional survey and there is no guarantee that any problems will be found or will be identified correctly and no liability lies with the researcher in this aspect. You will end up with a freely improved/insulated floor at the end of the study.

What else?

- **Your participation is voluntary and you have the right to withdraw at any time**
- Any information obtained will be anonymous and is just for research purposes.
- If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form.
- Please discuss the information above with others if you wish or ask the researcher if there is anything that is not clear or if you would like more information.
- It is up to you to decide whether to take part or not; choosing not to take part will not disadvantage you in any way. If you do decide to take part you are still free to withdraw at any time and without giving a reason.

Informed consent form example

Informed consent form for participants in research studies

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Project: Measuring heat-loss through pre-1919 suspended timber ground floors, before + after interventions
Researcher's name: Sofie Pelsmakers
Work address: xxxx
Contact details: Tel: xxxx

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Participant's Statement

1. I comfirm that I have read the notes written above and the **Information Sheet**, and understand what the study involves. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. If I have further queries about the study, I know I can get in touch with the researchers through the above contact details.
2. I understand that my participation in the study is entirely **voluntary** and that if I decide at any time that I no longer wish to take part in this project, I can notify the researcher and **withdraw** immediately, without giving reason. In the event that I withdraw from the study, any collected data will be kept by the researcher, and associated analysis will still be made. I will allow the researcher to come and collect any dataloggers/instruments in my property, which remain property of the researcher at all times.
3. I hereby agree to **participate** in the research study, which involves the researcher undertaking the monitoring and interventions for ~ 12-14 weeks, as described in the information sheet.
4. No personal data will be collected and any collected non-personal data will be **anonymised** and treated as **confidential**.
5. I understand that the information collected will be used and retained for the length of the study and beyond this (see point 6) and I can have **access** to the findings as described in the information sheet.
6. I agree that the data collected may be used by others for future research beyond the length of the study or the researcher's study time. I am assured that confidentiality will be upheld.
7. I understand that the data collected belongs to the project and that this information can be used by the researcher in **presentations and publications** and I can obtain a copy upon request. Confidentiality and anonymity will be maintained and it will not be possible to identify me from any publications.
8. I understand that digital photo's may be taken of wall and floor surfaces and the floor void but will never show any personal or private effects or any objects or identifiable property. I understand that I can obtain **access to any images** at any time and that I have the right to ask any to be deleted.
9. *I understand and agree that if the researcher has evidence suggesting an unhealthy structure, the researcher will inform me.* However, I understand that this is not a professional survey and there is no guarantee that problems will be found or will be identified correctly nor that liability rests with the researcher. The researcher is covered by UCL's Public Liability Insurance to undertake this field-work.

10. I agree that the research project named above has been explained to me to my satisfaction and **I agree to take part in this study.**

Name of participant: Signed:
Date:

Name of Researcher: Signed:
Date:

Health & safety risk assessment

RISK ASSESSMENT FORM
FIELD / LOCATION WORK

The Approved Code of Practice - Management of Fieldwork should be referred to when completing this form
http://www.ucl.ac.uk/estates/safetynet/guidance/fieldwork/acop.pdf

DEPARTMENT/SECTION UCL ENERGY INSTITUTE
LOCATION(S) UNOCCUPIED CASE STUDY HOUSE
PERSONS COVERED BY THE RISK ASSESSMENT Sofie Pelsmakers (PhD researcher), Home owner. Any research 'helpers' or supervisors will also be given a copy of this Risk assessment

--------------------------------LEAVE COPY OF THIS RISK ASSESSMENT ON SITE--

BRIEF DESCRIPTION OF FIELDWORK Measuring heat-loss of the building fabric, including undertaking interventions on the floor, such as lifting floorboards, placing insulation in between floor joists, removing carpet. Reearch to take place November 2013 to March 2014.

Consider, in turn, each hazard (white on black). If **NO** hazard exists select **NO** and move to next hazard section.
If a hazard does exist select **YES** and assess the risks that could arise from that hazard in the risk assessment box.
Where risks are identified that are not adequately controlled they must be brought to the attention of your Departmental Management who should put temporary control measures in place or stop the work. Detail such risks in the final section.

ENVIRONMENT	**The environment always represents a safety hazard. Use space below to identify and assess any risks associated with this hazard**
e.g. location, climate, terrain, neighbourhood, in outside organizations, pollution, animals.	Examples of risk: adverse weather, illness, hypothermia, assault, getting lost. Is the risk high / medium / low ? LOW RISK: cold environment to start with (dress appropriately), unknown neighbourhood and entering an unknown property (assign buddy's of whereabouts)

CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☐	work abroad incorporates Foreign Office advice
☒	participants have been trained and given all necessary information
☐	only accredited centres are used for rural field work
☒	participants will wear appropriate clothing and footwear for the specified environment
☐	trained leaders accompany the trip
☐	refuge is available
☐	work in outside organisations is subject to their having satisfactory H&S procedures in place
☒	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

Have a research 'helper' assist or use of Buddy scheme: 2 assigned people will be informed of time of arrival at the address and when expected to leave, and when having left, all via phone, with communication at regular intervals, with emergency procedures if researcher fails to make contact at the appointed time. [make sure phone fully charged].

EMERGENCIES	**Where emergencies may arise use space below to identify and assess any risks**
e.g. fire, accidents	Examples of risk: loss of property, loss of life

LOW RISK: unoccupied property to be electrically heated: all heating equipment to be PAT tested at UCL prior to use. Ensure equipment/instruments covered by UCL insurance and Public Liability Insurance in place (confirmed by June Campbell 27.11.2013)

CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☐	participants have registered with LOCATE at http://www.fco.gov.uk/en/travel-and-living-abroad/
☐	fire fighting equipment is carried on the trip and participants know how to use it
☒	contact numbers for emergency services are known to all participants
☒	participants have means of contacting emergency services

☐	a plan for rescue has been formulated, all parties understand the procedure
☐	the plan for rescue /emergency has a reciprocal element
☒	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

PAT Testing equipment; make neighbours aware of the work being undertaken to keep eye out. Put heaters on heat mats; portable fire alarms. Check electrical circuit vs heating output required. Ensure electricity board of dwelling tested and safe (RCD).

FIELDWORK 1 May 2010

EQUIPMENT	**Is equipment used?**	**Yes**	**If 'No' move to next hazard** **If 'Yes' use space below to identify and assess any risks**
e.g. clothing, outboard motors.	Examples of risk: inappropriate, failure, insufficient training to use or repair, injury. Is the risk high / medium / low ?		

LOW RISK: PAT Testing of electrical heating equipment prior to use. Some heavy equipment to be located in the house - transport via taxi and ask for a research helper. Some floor board lifting may need to be undertaken by researcher: use endoscope/IR camera to ensure no damage to any services in the void. Ensure technique is safe + as agreed with home owner. If in doubt, get specialist builder/worker in, which is preferred in any case.

CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☐	the departmental written Arrangement for equipment is followed
☒	participants have been provided with any necessary equipment appropriate for the work
☒	all equipment has been inspected, before issue, by a competent person
☒	all users have been advised of correct use
☒	special equipment is only issued to persons trained in its use by a competent person
☒	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

Get specialist builder in to undertake any manual /sensitive work; transport heavy kit via taxi and get helpers.

LONE WORKING	**Is lone working a possibility?**	**Yes**	**If 'No' move to next hazard** **If 'Yes' use space below to identify and assess any risks**
e.g. alone or in isolation lone interviews.	Examples of risk: difficult to summon help. Is the risk high / medium / low?		

LOW RISK: researcher has assigned 2 buddy's to know of whereabouts (see 'environment'); the local Society is also aware of the work being undertaken. In addition to the buddy's being informed of whereabouts; researcher will inform homeowner IN ADVANCE of entering property; upon entering + when leaving.

☒	the departmental written Arrangement for lone/out of hours working for field work is followed
☐	lone or isolated working is not allowed
☐	location, route and expected time of return of lone workers is logged daily before work commences
☒	all workers have the means of raising an alarm in the event of an emergency, e.g. phone, flare, whistle
☐	all workers are fully familiar with emergency procedures
☒	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

as stated above (ask helper and where not possible, use of buddy scheme) + when accessing any confined space such as floor void, this will not be done while alone in the premises but with a helper. Carry personal alarm.

ILL HEALTH	**The possibility of ill health always represents a safety hazard. Use space below to identify and assess any risks associated with this Hazard.**
e.g. accident, illness, personal attack, special personal considerations or vulnerabilities.	Examples of risk: injury, asthma, allergies. Is the risk high / medium / low? LOW RISK: injury from lifting heavy equipment or lifting floorboards or trip hazard over equipment leads.injury from falling from a chair or a small step-ladder when installing equipment.
CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☐	an appropriate number of trained first-aiders and first aid kits are present on the field trip
☐	all participants have had the necessary inoculations/ carry appropriate prophylactics
☐	participants have been advised of the physical demands of the trip and are deemed to be physically suited
☐	participants have been adequate advice on harmful plants, animals and substances they may encounter
☐	participants who require medication have advised the leader of this and carry sufficient medication for their needs
☒	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

Move heavy equipment via taxi/get helper and tape down equipment leads to avoid trip hazard. Ensure good lighting in house.

TRANSPORT	**Will transport be required**	**NO**		**Move to next hazard**
		YES		**Use space below to identify and assess any risks**
e.g. hired vehicles	Examples of risk: accidents arising from lack of maintenance, suitability or training Is the risk high / medium / low? LOW RISK			

CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☒	only public transport will be used
☐	the vehicle will be hired from a reputable supplier
☐	transport must be properly maintained in compliance with relevant national regulations
☐	drivers comply with UCL Policy on Drivers http://www.ucl.ac.uk/hr/docs/college_drivers.php
☐	drivers have been trained and hold the appropriate licence
☐	there will be more than one driver to prevent driver/operator fatigue, and there will be adequate rest periods
☐	sufficient spare parts carried to meet foreseeable emergencies
☒	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

Or use of taxi.

DEALING WITH THE PUBLIC	**Will people be dealing with public**	**Yes**	**If 'No' move to next hazard** **If 'Yes' use space below to identify and assess any risks**
e.g. interviews, observing	Examples of risk: personal attack, causing offence, being misinterpreted. Is the risk high / medium / low? LOW RISK : leafletting in the area (~ 200 homes) by putting leaflets through letterboxes. Local Brentham Society is aware of this + the work taking place; have someone accompany researcher and/or buddy scheme.		

CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☐	all participants are trained in interviewing techniques
☐	interviews are contracted out to a third party
☒	advice and support from local groups has been sought
☒	participants do not wear clothes that might cause offence or attract unwanted attention
☐	interviews are conducted at neutral locations or where neither party could be at risk
☒	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

WORKING ON OR NEAR WATER	**Will people work on or near water?**	**No**	**If 'No' move to next hazard** **If 'Yes' use space below to identify and assess any risks**
e.g. rivers, marshland, sea.	Examples of risk: drowning, malaria, hepatitis A, parasites. Is the risk high / medium / low?		

CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☐	lone working on or near water will not be allowed
☐	coastguard information is understood; all work takes place outside those times when tides could prove a threat
☐	all participants are competent swimmers
☐	participants always wear adequate protective equipment, e.g. buoyancy aids, wellingtons
☐	boat is operated by a competent person
☐	all boats are equipped with an alternative means of propulsion e.g. oars
☐	participants have received any appropriate inoculations
☐	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

MANUAL HANDLING (MH)	**Do MH activities take place?**	**Yes**	**If 'No' move to next hazard** **If 'Yes' use space below to identify and assess any risks**
e.g. lifting, carrying, moving large or heavy equipment, physical unsuitability for the task.	Examples of risk: strain, cuts, broken bones. Is the risk high / medium / low? LOW RISK - lifting boxes/heavy equipment		

CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☐	the departmental written Arrangement for MH is followed
☐	the supervisor has attended a MH risk assessment course
☒	all tasks are within reasonable limits, persons physically unsuited to the MH task are prohibited from such activities
☐	all persons performing MH tasks are adequately trained
☒	equipment components will be assembled on site
☐	any MH task outside the competence of staff will be done by contractors
☒	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

Get helper to help lift; package manageable weights (so more smaller boxes rather than a few big heavy ones)

SUBSTANCES	**Will participants work with substances**	**No**	**If 'No' move to next hazard** **If 'Yes' use space below to identify and assess any risks**
e.g. plants, chemical, biohazard, waste	Examples of risk: ill health - poisoning, infection, illness, burns, cuts. Is the risk high / medium / low?		

CONTROL MEASURES	**Indicate which procedures are in place to control the identified risk**
☐	the departmental written Arrangements for dealing with hazardous substances and waste are followed
☐	all participants are given information, training and protective equipment for hazardous substances they may encounter
☐	participants who have allergies have advised the leader of this and carry sufficient medication for their needs
☐	waste is disposed of in a responsible manner
☐	suitable containers are provided for hazardous waste
☐	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

OTHER HAZARDS	**Have you identified any other hazards?**	**Yes**	**If 'No' move to next section** **If 'Yes' use space below to identify and assess any risks**
i.e. any other hazards must be noted and assessed here.	Hazard: accidental damage to 3rd party property Risk: is the risk	**low**	

CONTROL MEASURES	**Give details of control measures in place to control the identified risks**

No research equipment will be moved in until familiarised with property + what is needed and where. No intervention will take place without discussion and agreement with home owner; if damage to property or person is likely the research will be postponed or cancelled until safe to person and property. Only appropriate persons to handle instruments and tools for floor board lifting and interventions.

Have you identified any risks that are not adequately controlled?	**NO**	☒	**Move to Declaration**
	YES	☐	**Use space below to identify the risk and what action was taken**

Is this project subject to the UCL requirements on the ethics of Non-NHS Human Research? No

If yes, please state your Project ID Number

For more information, please refer to: http://ethics.grad.ucl.ac.uk/

DECLARATION	The work will be reassessed whenever there is a significant change and at least annually. Those participating in the work have read the assessment.

Select the appropriate statement:

☒ I the undersigned have assessed the activity and associated risks and declare that there is no significant residual risk

☒ I the undersigned have assessed the activity and associated risks and declare that the risk will be controlled by the method(s) listed above

NAME OF SUPERVISOR Sofie Pelsmakers

Appendix 5.B. Additional field study limitations

Additional field study limitations and issues are identified below:

- **Ground heat-flux and temperatures** were measured with HFP01 sensors in two locations: under location 22 (2 heat-fluxes in this location) and under location 5, excluding ground temperatures. HFP01 sensors are not intended for soil measurements and have a lower accuracy (±15%,(Bos, 2012)); no access to soil heat-fluxes was available and the average of two HFP01 sensors should be used instead (Bos, 2012), however the paired heat-fluxes were wildly differing despite being located next to each other. One sensor gave 200% higher readings and even averaging sensors was unreliable and hence of limited use. This might be explained by great difficulty in placement of sensors under a thin layer of dust and rubble (25-45 mm) on top of oversite concrete; it is unclear what was measured and how airflow in rubble pockets around all sensors affected measurements.
- **Foundation wall heat-fluxes** were attempted to be measured on the kitchen/living room foundation wall, external foundation wall and foundation party wall to understand direction of heat flow and in the case of the external foundation wall, to estimate its U-value for use in a model. However due to the roughness of the brick foundation walls and the sensor being slightly larger than a typical brick surface, sensors lost contact with the wall surfaces despite exploring different fixing methods; hence directional heat flow or U-values could not be derived. One sensor was also placed at the bottom of the a joist in the floor void but also lost contact and fell down.
- **kWh electricity readers:** KWh meter readers were initially used to log the energy used by the radiators to allow for comparison with external weather conditions and between interventions and to isolate space-heating energy use from other electricity use (lighting/equipment). One kWh reader in the living room developed an electrical fault and disabled heating in this room between December 30th to January 3rd, and lead to the late start of the study. All kWh readers were removed to avoid future problems and space-heating was reinstated on January 3rd.

Appendix 5.C: Chauvenet's Criterion for outlier removal

OPEN AIRBRICKS							
Location	**Uninsulated floor-mean U** Wm^2K^{-1}	**Sd** Wm^2K^{-1}	**Uninsulated floor-outliers removed - mean U** Wm^2K^{-1}	**sd-outliers removed** Wm^2K^{-1}	**% difference U**	**% difference sd**	**hrs removed**
HF1	1.77	0.10	1.74	0.09	2	10	8
HF2	1.65	0.11	1.62	0.10	2	5	9
HF3	1.27	0.09	1.25	0.08	2	7	6
HF4	0.67	0.08	0.66	0.06	1	20	6
HF5	0.55	0.08	0.54	0.07	2	18	6
HF6	2.06	0.11	2.04	0.10	1	13	10
HF7	1.65	0.12	1.62	0.12	1	1	7
HF8	1.38	0.11	1.37	0.10	1	7	7
HF9	1.13	0.11	1.11	0.10	1	10	5
HF10	1.00	0.10	0.99	0.09	1	10	5
HF11	0.78	0.08	0.78	0.07	1	11	3
HF12	0.70	0.08	0.69	0.07	1	11	3
HF13	0.60	0.08	0.60	0.07	1	10	3
HF14	1.16	0.07	1.14	0.06	2	14	7
HF15	1.23	0.07	1.21	0.05	2	24	7
HF16	1.14	0.07	1.13	0.05	1	23	5
HF17	1.01	0.07	0.99	0.05	2	21	6
HF18	1.02	0.07	1.01	0.06	1	21	4
HF19	0.91	0.08	0.90	0.07	2	12	5
HF20	0.81	0.07	0.80	0.06	1	17	4
HF21	0.60	0.08	0.60	0.07	1	11	3
HF22	2.02	0.12	1.99	0.11	2	13	8
HF23	1.24	0.10	1.21	0.08	2	16	6
HF24	0.98	0.08	0.96	0.07	2	15	5
HF25	0.75	0.08	0.75	0.07	1	12	4
HF26	0.67	0.08	0.66	0.08	1	11	3
HF_Joist 13b	0.51	0.06	0.51	0.05	1	15	6

Table 53.Comparison of U-value and sd estimation with and without outliers removed for the uninsulated floor (open airbricks) with % differences.

SEALED AIRBRICKS							
Location	**Uninsulated floor-mean U** Wm^2K^{-1}	**Sd** Wm^2K^{-1}	**Uninsulated floor-outliers removed - mean U** Wm^2K^{-1}	**sd-outliers removed** Wm^2K^{-1}	**% difference U**	**% difference sd**	**hrs removed**
HF1	0.94	0.18	0.94	0.14	1	21	6
HF2	0.99	0.19	1.00	0.16	0	17	5
HF3	0.82	0.17	0.82	0.15	0	13	4
HF4	0.58	0.12	0.57	0.11	2	6	2
HF5	0.52	0.12	0.52	0.11	0	7	2
HF6	0.81	0.19	0.80	0.16	1	13	3
HF7	0.86	0.19	0.87	0.15	-1	19	5
HF8	0.77	0.14	0.75	0.13	2	10	3
HF9	0.71	0.15	0.70	0.13	2	13	4
HF10	0.66	0.14	0.64	0.12	3	10	3
HF11	0.61	0.13	0.60	0.12	2	7	2
HF12	0.60	0.13	0.59	0.12	2	6	2
HF13	0.53	0.12	0.53	0.11	0	7	2
HF14	0.86	0.18	0.87	0.14	-1	27	6
HF15	0.91	0.17	0.90	0.14	2	13	4
HF16	0.78	0.15	0.76	0.13	3	15	4
HF17	0.75	0.15	0.73	0.14	3	12	3
HF18	0.71	0.15	0.69	0.13	3	14	3
HF19	0.72	0.15	0.71	0.14	2	7	2
HF20	0.61	0.13	0.59	0.11	3	12	3
HF21	0.56	0.12	0.55	0.11	2	7	2
HF22	1.03	0.26	1.06	0.20	-3	22	6
HF23	0.90	0.14	0.84	0.13	6	6	5
HF24	0.77	0.14	0.75	0.12	3	14	3
HF25	0.63	0.13	0.62	0.12	2	6	2
HF26	0.59	0.13	0.58	0.12	2	7	2
HF_Joist 13b	0.46	0.10	0.45	0.09	2	8	3

Table 54. Comparison of U-value and sd estimation with and without outliers removed for the uninsulated floor with airbricks sealed.

Appendix 5.D: Changing environmental conditions for sealing of airbricks.

Environmental conditions	**Uninsulated - open airbricks** (13 days, mid-January to late January 2014)	**Uninsulated - sealed airbricks** (4 days, early January 2014)
% of time ≤15°C external (based on hourly data)	100%	100%
Mean external temperature	6.2 ±0.1 °C	7.9 ±0.1 °C
Mean wind-speed	0.41 ±0.2 m/s	0.77 ±0.2 m/s
void airflow (below location 6)	0.44 ±0.12 m/s	0.09±0.12m/s
Mean solar radiation	227 ±23W/m^2	139 ±14W/m^2
Soil temperature 1000mm away from house at 300 mm depth	7.1 ±0.1 °C	8.2 ±0.1 °C
Possible confounding influences on estimated U-values?	During the sealed airbrick monitoring period there was (a.) increased wind-speed: this is likely to have had minimal effect as airbricks were sealed; (some minor effect on reduced external wall surface resistances & if cold air infiltrated through other gaps and cracks) so might underestimate efficacy of airbrick sealing; and (b.) increased external temperatures and ground temperatures might lead to (unknown) changes in ground thermal mass storage but this might have been offset by decreased solar radiation. It is unknown what the overall effects might be.	

Table 55. presents the environmental conditions for each monitoring interval pre-post airbrick sealing.

Appendix 5.E: Comparison of estimated U-value reduction in each point location for the uninsulated floor compared to airbrick sealing.

Location	Uninsulated floor- mean U (outliers removed; final error) ($Wm^{-2}K^{-1}$)			*final error (%)*	**% reduction from open airbricks**
HF1	0.94	±	0.17	*18*	**46**
HF2	1.00	±	0.18	*18*	**38**
HF3	0.82	±	0.17	*20*	**34**
HF4	0.57	±	0.12	*21*	**14**
HF5	0.52	±	0.12	*23*	**4**
HF6	0.80	±	0.18	*22*	**61**
HF7	0.87	±	0.17	*20*	**47**
HF8	0.75	±	0.15	*20*	**45**
HF9	0.70	±	0.15	*21*	**38**
HF10	0.64	±	0.14	*21*	**35**
HF11	0.60	±	0.13	*22*	**23**
HF12	0.59	±	0.13	*23*	**15**
HF13	0.53	±	0.12	*23*	**11**
HF14	0.87	±	0.16	*18*	**24**
HF15	0.90	±	0.17	*18*	**26**
HF16	0.76	±	0.15	*20*	**33**
HF17	0.73	±	0.15	*21*	**26**
HF18	0.69	±	0.14	*21*	**31**
HF19	0.71	±	0.15	*21*	**21**
HF20	0.59	±	0.12	*21*	**26**
HF21	0.55	±	0.12	*23*	**7**
HF22	1.06	±	0.22	*21*	**47**
HF23	0.84	±	0.15	*18*	**31**
HF24	0.75	±	0.14	*19*	**22**
HF25	0.62	±	0.13	*22*	**17**
HF26	0.58	±	0.13	*23*	**12**
HF_Joist_13b	0.45	±	0.10	*23*	**12**

Table 56. Comparison of estimated U-value reduction in each point location for the uninsulated floor compared to airbrick sealing.

Appendix 6.A: Intervention pilot study (STUDY 3)

This exploratory study was described in Chapter 6.2, alongside main insights gained, which were mainly related to measuring techniques and reducing pre/post intervention measurement uncertainties. These lessons were taken into account and informed the main field intervention study. Further detail is provided below.

Main issues	Insights gained & how to mitigate in main field study
External environmental conditions (i.e. measuring heat-flow outside the heating season)	Despite heating the internal space, due to the period of the year (late summer/early autumn) minimal temperature differences were observed. The seasonal thermal mass behaviour of the ground was unknown, and cannot be controlled for or evaluated unless monitoring occurs over a long period of time, which requires long-term access and is outside the scope of a main field study. Monitoring should occur in the winter heating season and regular site visits and data collection should highlight ΔT issues.
Changing environmental conditions as confounding variables	No wind-speeds or solar radiation were recorded, which made pre/post comparisons more challenging: did the change in heat flow occur due to the intervention or other environmental variables changing? Monitoring such variables would be useful to qualitatively compare pre/post intervention conditions and how these may affect results.
Insufficient shielding of solar gain	Direct solar gain affected the internal and possibly also one of the external sensors due to insufficient solar shielding with a changing solar angle over time. In the post-intervention stage reflective foil was taped over the entire window, creating significantly different pre/post intervention conditions and affecting comparability between pre/post findings. Thus installing temporary curtains or blinds for the duration of the study will block out all direct solar gain and solar reflections, minimising direct effects on heat-flow in pre/post studies and limiting changing variables between interventions.
Difficulty to replicate sensor placement pre-post intervention	Exact sensor location was surveyed by measuring from the *centre* of the sensors to a reference wall. However, this procedure increased the measurement error for sensors far from the reference wall and made it difficult to exactly relocate them. Instead, sensor locations should be noted from the nearest *edges* of the sensor to the *nearest* perpendicular wall distance.
Infrequency of data collection	Access could only be gained at the start and at the end of each pre- and post- intervention stage. This limited the ability to check progress and prevent unforeseen problems, which would have lead to more robust data collection (such as an external sensor which stopped functioning, small ΔT). Regular access, and more frequent data collection and checking are crucial for field studies. Remote logging is likely to support this process but will depend on equipment availability and specification.
Other works taking place and interfering with data collection	Other major works were taking place during the 2 monitoring phases, thus monitoring could have been disturbed by accidentally changing internal conditions, even if staff were instructed to avoid entering the living room.
Absence during insulation installation	Due to the pilot study house location, it was not possible to directly monitor insulation installation; in addition there was a shortage of insulation material and additional insulation had to be bought from a different source and with different specification. The placement of different insulations was not recorded at installation, adding significant uncertainty about installation quality and interpretation of post-intervention differences between points on the floor. Mobile phone pictures sent from site at installation did not provide enough detail to remedy this issue.
Change in floor finish	The existing floorboards were replaced entirely with tongue and grooved chipboard, changing the material conductivity of the floor finish and making the floor structure more airtight post-intervention; keeping variables the same pre-post intervention is preferable.
point measurements	Both limited void access could be obtained and only a few points on the floor could be monitored; only a few weeks pre and post insulation were monitored. Additionally, high-resolution heat-flux monitoring is required to obtain a whole floor U-value pre/post insulation and for comparison with models. While such comparisons were not the purpose of this study, the limitation of low resolution monitoring was reiterated.

Table 57. Insights gained from the exploratory pre-post intervention study - summary table

Appendix 6.B: bead-insulated floor and U-values over different monitoring periods

In bold + grey highlight where all ISO-9869 tests were met

Location	Final Umean	Sd	15 days U mean	15 days sd	12 days U mean	12 days sd	9 days U mean	9 days sd	8 days U mean	8 days sd	6 days U mean	6 days sd	5 days U mean	5 days sd
	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K	W/m2K
U1	**0.25**	0.06	0.26	0.05	0.25	0.06	**0.25**	0.06	0.25	0.06	0.23	0.05	0.23	0.06
U2	**0.09**	0.02	0.09	0.02	0.09	0.02	**0.09**	0.02	0.09	0.02	0.09	0.02	0.09	0.02
U3	**0.08**	0.01	0.08	0.01	0.09	0.01	**0.08**	0.01	0.09	0.02	0.08	0.02	0.08	0.02
U4	**0.07**	0.01	0.07	0.01	0.07	0.01	**0.07**	0.01	0.07	0.01	0.07	0.01	0.07	0.01
U5	**0.10**	0.02	0.11	0.02	0.11	0.02	**0.10**	0.02	0.10	0.01	0.10	0.01	0.10	0.02
U6	**0.58**	0.24	0.65	0.24	0.60	0.23	**0.58**	0.24	0.61	0.24	0.52	0.16	0.50	0.17
U7	**0.07**	0.03	0.08	0.02	0.08	0.02	**0.07**	0.03	0.08	0.03	0.06	0.02	0.07	0.02
U8	**0.08**	0.02	0.08	0.02	0.09	0.02	**0.08**	0.02	0.08	0.02	0.08	0.02	0.08	0.02
U9	**0.02**	0.01	0.03	0.01	0.03	0.01	**0.02**	0.01	0.02	0.02	0.02	0.01	0.02	0.02
U10	**0.06**	0.02	0.06	0.01	0.06	0.02	**0.06**	0.02	0.06	0.02	0.05	0.02	0.05	0.02
U11	**0.04**	0.01	0.04	0.01	0.04	0.01	**0.04**	0.01	0.04	0.01	0.03	0.01	0.03	0.01
U12	**0.06**	0.01	0.06	0.01	0.06	0.01	**0.06**	0.01	0.06	0.01	0.06	0.01	0.06	0.01
U13	**0.17**	0.05	**0.17**	0.05	0.18	0.06	0.17	0.06	0.15	0.04	0.15	0.04	0.15	0.04
U14	**0.15**	0.05	0.16	0.05	**0.15**	0.05	0.13	0.05	0.14	0.05	0.12	0.05	0.13	0.06
U15	**0.09**	0.03	0.12	0.03	0.11	0.03	0.10	0.03	0.10	0.03	**0.09**	0.03	0.08	0.03
U16	**0.08**	0.02	0.10	0.02	0.10	0.03	0.09	0.02	0.09	0.03	**0.08**	0.02	0.08	0.02
U17	**0.04**	0.01	0.05	0.01	0.05	0.01	**0.04**	0.01	0.04	0.01	0.04	0.01	0.04	0.01
U18	**0.07**	0.01	0.07	0.01	0.07	0.01	**0.07**	0.01	0.07	0.01	0.06	0.01	0.06	0.01
U19	**0.02**	0.01	0.02	0.01	0.02	0.01	**0.02**	0.01	0.02	0.01	0.02	0.01	0.02	0.01
U20	**0.06**	0.01	0.07	0.01	0.07	0.01	**0.06**	0.01	0.06	0.01	0.06	0.01	0.06	0.01
U21	**0.17**	0.05	0.17	0.05	0.19	0.05	0.18	0.06	**0.17**	0.05	0.18	0.05	0.18	0.06
U22	**0.25**	0.10	0.29	0.11	0.26	0.10	**0.25**	0.10	0.26	0.10	0.23	0.08	0.22	0.08
U23	**0.06**	0.03	0.06	0.02	**0.06**	0.03	0.06	0.03	0.06	0.03	0.04	0.01	0.04	0.01
U24	**0.05**	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.06	0.02	0.05	0.02	**0.05**	0.02
U25	**0.06**	0.01	0.06	0.01	0.06	0.01	**0.06**	0.01	0.06	0.01	0.05	0.01	0.05	0.01
U26	**0.18**	0.07	0.19	0.08	0.20	0.08	0.20	0.08	**0.18**	0.07	0.20	0.07	0.19	0.08
MEAN	**0.11**	0.04	**0.12**	0.04	**0.12**	0.04	**0.12**	0.04	**0.12**	0.04	**0.11**	0.03	**0.11**	0.03
Joist 13b	0.18	0.04	0.18	0.04	0.19	0.04	**0.18**	0.04	0.17	0.04	0.18	0.04	0.17	0.05

Table 58. bead-insulated floor and U-values over different monitoring periods. Presents estimated U-values and their standard deviation (sd) at different monitoring periods for the bead-insulated floor; final estimated U-values used in this thesis highlighted in bold (when both ISO-9869 tests were met); they are not significantly different from those obtained at other monitoring periods.

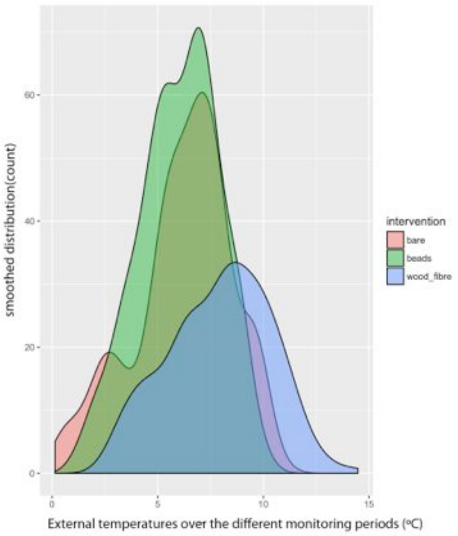
Appendix 6.C: Changing environmental conditions during woodfibre intervention - sealed airbricks

Different environmental conditions occurred pre-post sealing of airbricks and this may have affected the comparisons. Though its exact quantity is unknown, the efficacy of the airbrick closure might be slightly underestimated for the wood fibre insulated floor - see *Table 16*.

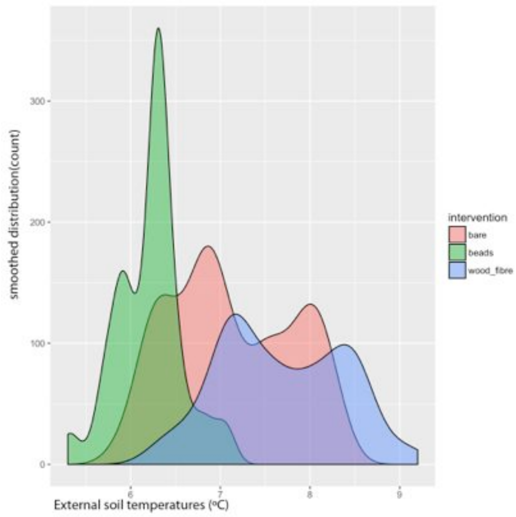
Environmental conditions	**woodfibre insulated - open airbricks (9 days)**	**woodfibre insulated - sealed airbricks (5 days)**
% of time ≤15ºC external (based on hourly data)	100%	85%
Mean external temperature	10.7 ±0.1 ºC	10.9 ±0.1 ºC
Mean wind-speed	0.57 ±0.2 m/s	0.63 ±0.2 m/s
void airflow (below location 6)	0.78 ±0.12 m/s	0.13±0.12m/s
Mean solar radiation	379 ±38W/m^2	810 ±81W/m^2
Soil temperature 1000mm away from house at 300 mm depth	7.7 ±0.1 ºC	9.1 ±0.1 ºC
Possible confounding influences on estimated U-values?	The external conditions were similar pre/post airbrick sealing; however the soil temperature and mean solar radiation were significantly higher when airbricks were sealed; it is unknown what effect this may have had, but might lead to warming up of the ground and possibly leading to a warmer floor void, reducing the rate of heat-flow and possibly underestimating the efficacy (impact) of sealed airbricks.	

Table 59. Changing environmental conditions during woodfibre intervention - sealed airbricks: presents the environmental conditions for each monitoring interval pre/post airbrick sealing for the woodfibre intervention.

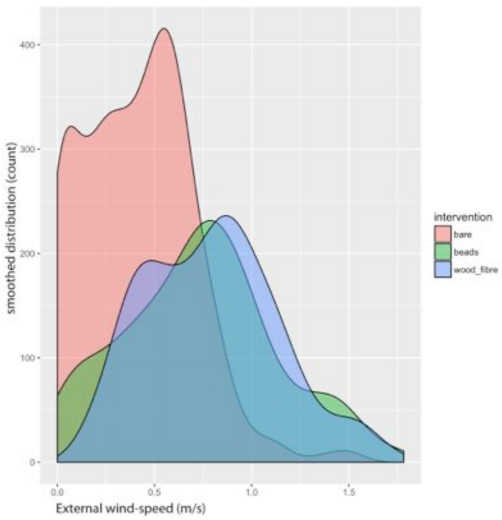
Appendix 6.D: Histogram plots of changing external variables during interventions



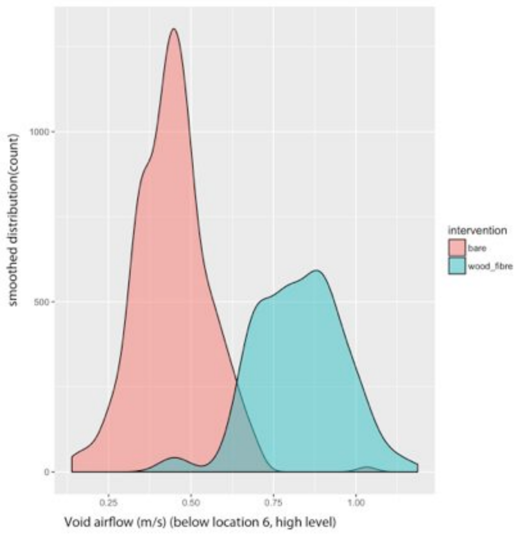
a.



b.



c.



d.

Figure 76. a., b., c. and d. Histograms with continuous distribution comparing hourly distribution of external temperatures (a.), ground temperature (b.), external wind speeds (c.) and void airflow under sensor location 6 (d.) for each of the monitored intervention periods of 13 days and 9 days for uninsulated floor (airbricks open) and bead and woodfibre uninsulated (airbricks open) floors respectively. Note that no void airflow was measured for the bead-intervention.

Appendix 6.E: Field study surface temperatures

As expected and as observed in the Salford EH, once insulated, the floor surface temperatures (including heated and unheated periods) increased by on average 1.8ºC for both interventions, though this might be overestimated for the woodfibre intervention given the warmer external temperatures during that monitoring period. On average surface temperatures were also 1.2ºC to 1.3ºC warmer with sealed airbricks for the uninsulated and woodfibre insulated floor respectively. Warmer floor surfaces are beneficial for occupant thermal comfort; however even when insulated, floor surface temperatures were below 19ºC; implications of this on thermal comfort are discussed in Chapter 6.5. Note that the figures below are based on mean surface temperatures of the full monitoring period, while the thermal comfort discussion is based on surface temperatures during occupied (heated) periods (when typically higher surface temperatures were observed).

As *Figure 77.*, *Figure 78* and *Figure 79.* Illustrate that the floor surfaces are significantly colder in the perimeter region (as low as 13ºC in the uninsulated floor) compared to the non-perimeter region (up to 16ºC in the uninsulated floor). The impact of interventions increases floor surface temperatures above average in the perimeter zone (by 2.0±0.14ºC to 2.1±0.14ºC compared to 1.6±0.14ºC to 1.7±0.14ºC for the non-perimeter zone for woodfibre and bead intervention respectively). The effect of the perimeter and airbrick airflow is much more significant in the uninsulated floor compared to the insulated floors; though *Figure 4.* also illustrates the effect of installation issues in location 3 and 21 - as described in Chapter 6.4.3.1.

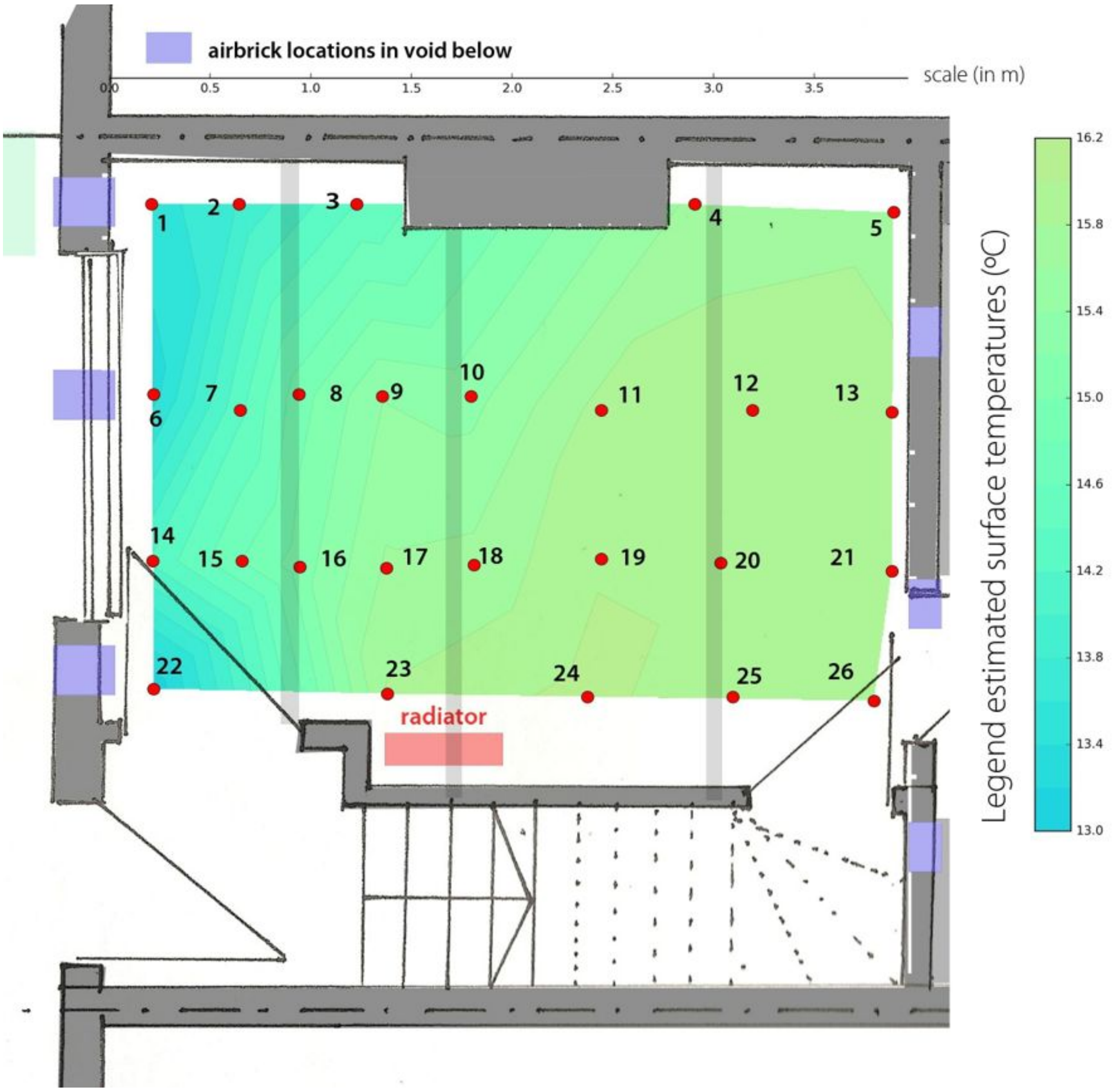


Figure 77. presents linearly interpolated surface temperatures for the uninsulated floor as a heat map between observed locations (marked with a red dot). Note that the map only shows interpolated values between points, no values between the walls and the points (hence the white zone); points are located off the map due to limitations of the model. The colour scale is the same for all the figures.

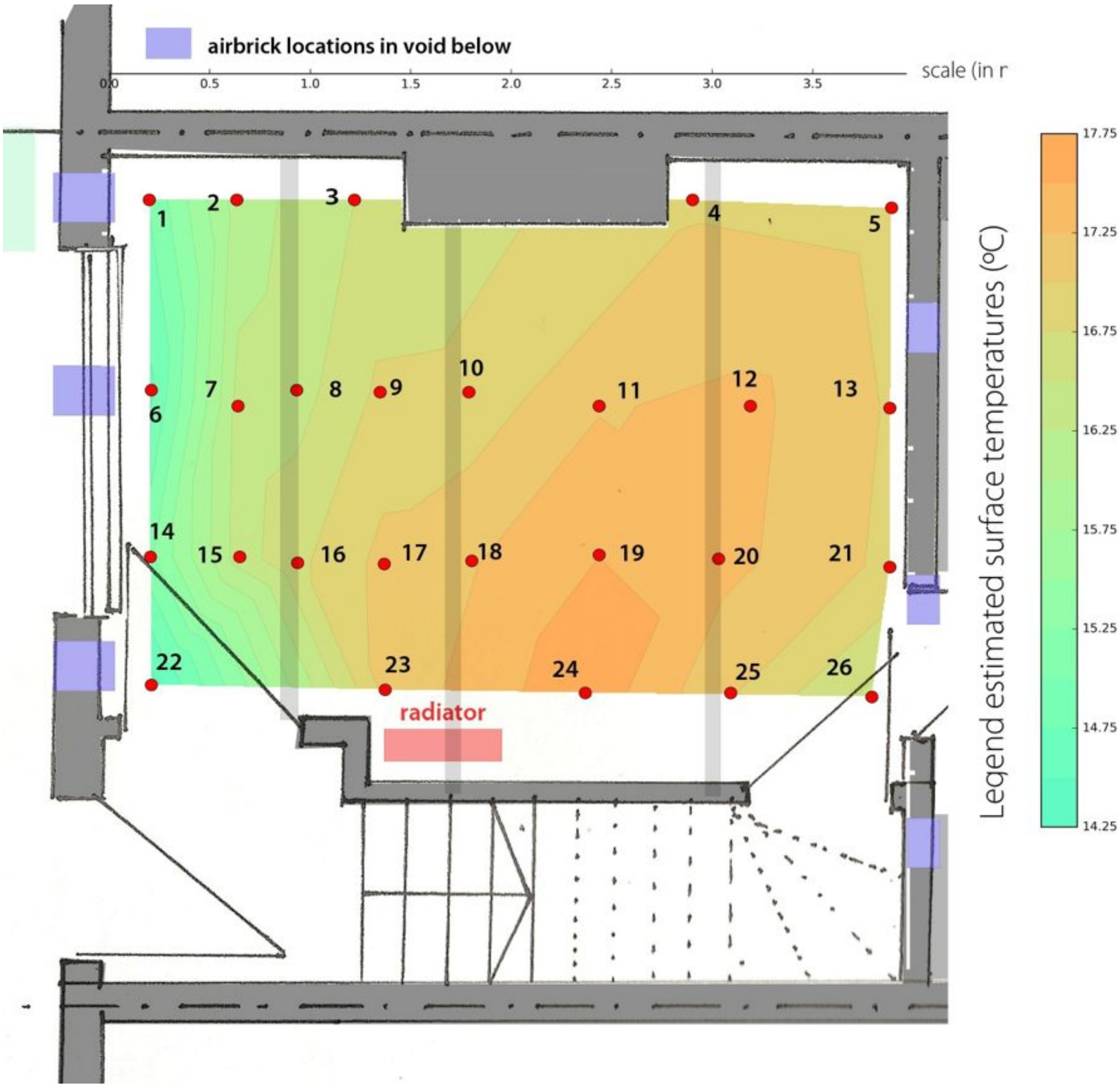


Figure 78. as previous figure but for bead insulated floor

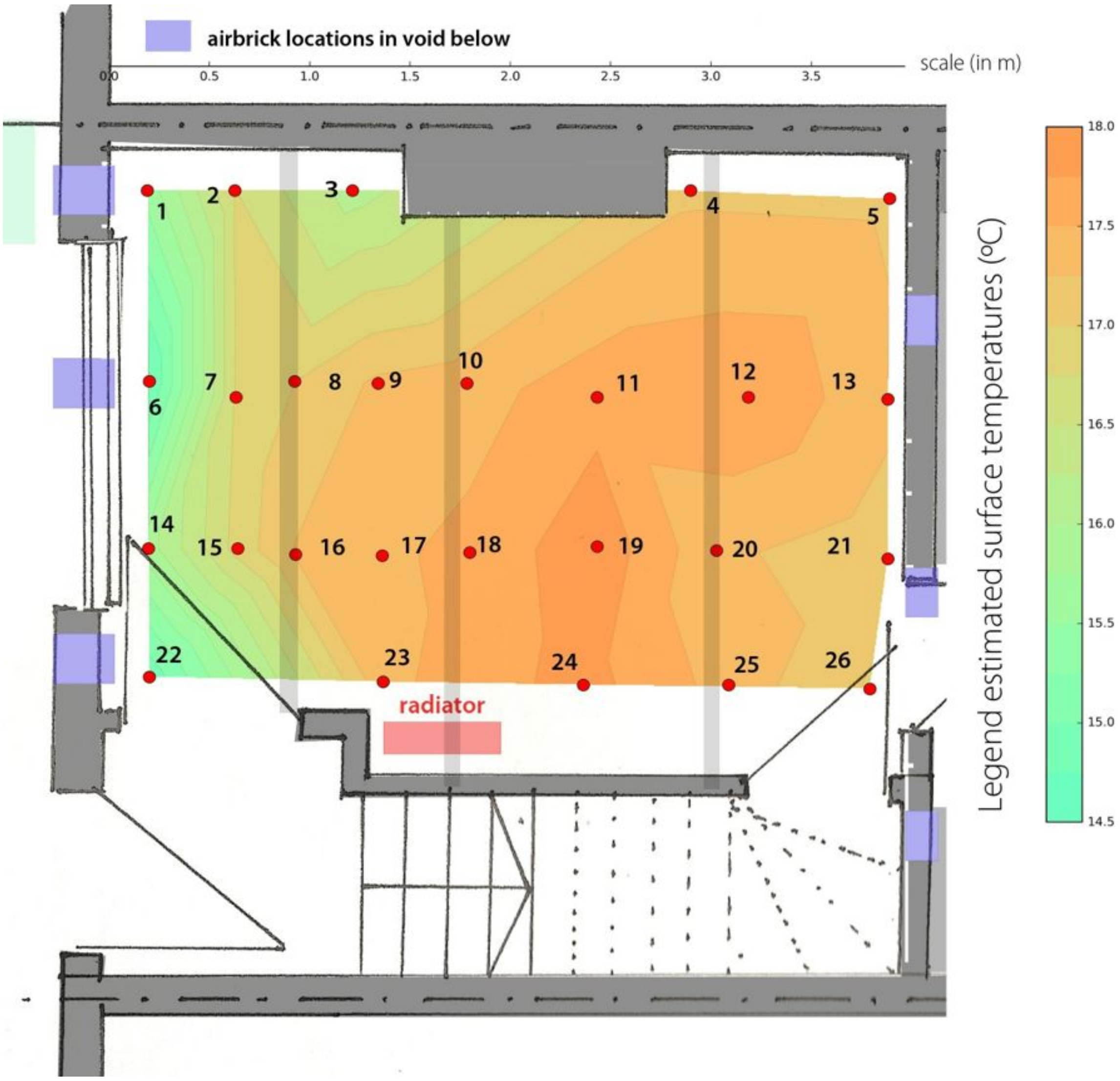


Figure 79. as previous figure but for woodfibre insulated floor